Physics near the conformal boundary in SU(3) gauge theory

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- at BNL RIKEN/HET joint seminar -

Jan. 9, 2014

NAGOYA UNIVERSITY

KMI

“Higgs boson”

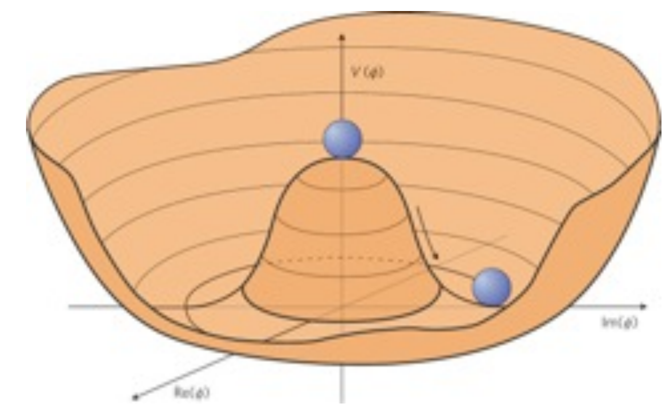
- Higgs boson fund at LHC
- m_H = 125 GeV
- so far consistent with Standard Model Higgs ($J^{PC}=0^{++}$) fundamental scalar
- but it could be different
- one of the possibilities:
  - composite Higgs
  - SM Higgs is the low energy effective description of that, cf: ChPT ⇔ QCD

Role of SM Higgs

- It's about the origin of mass...
- (99% of the mass of visible universe is made by QCD dynamics)
- masses of fundamental particles: quarks, leptons, weak bosons
  - by EW gauge symmetry breaking through Higgs

Higgs mechanism (cf. Farhi & Susskind)

- Higgs potential : $V=\mu^2 |\phi|^2 + \lambda|\phi|^4$ with $\mu^2<0$: “wine bottle”
    - rotating: $m=0$ mode
    - radial: $m\neq0$: Higgs particle



- weak doublet: 4 fields: 1 massive Σ, 3 massless
- massless: $\Pi^\pm$, Π^0 : Nambu-Goldstone boson (rotational symm. br.)
- have coupling to weak current: $\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$; $F = \langle 0|\phi|0\rangle = 246$ GeV
- make a massless pole in the vacuum polarization
- cancels massless pole of original $W^\pm$ propagator → massive gauge boson

$\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$

- Isn't it familiar ?   : $\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$ with massless boson $\Pi^\pm$
- pion decay: $\langle 0|A_\mu^\pm|\pi^\pm\rangle = f\, p_\mu$
    - $\pi^\pm\ \pi^0$ Nambu-Goldstone boson made of u, q quarks due to
    - $SU(2)_L x SU(2)_R \rightarrow SU(2)_V$: spontaneous chiral symmetry breaking
    - in the real world: pseudo NG boson
    - f=93 MeV ⇔ F=246 GeV
- axial current $A_\mu^\pm$ is a part of weak current $J_\mu^\pm$: (V-A)
- Even if there is no Higgs, weak boson gets massive due to chiral br. in QCD

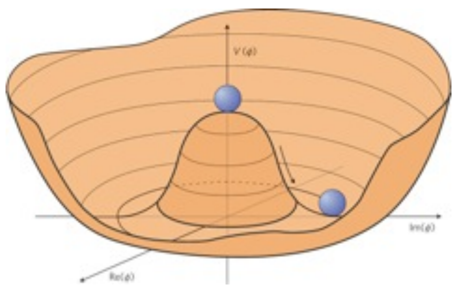
Technicolor (TC)

- $\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$
- realize this with a new set of
  - massless quarks (techni-quarks)
  - which have coupling to weak bosons,
  - and interact with techni-gluons
  - which breaks the chiral symmetry in the techni-sector,
  - produces techni-pions which have decay constant

➡$F = 246/\sqrt{N}$ GeV: scale up version of QCD (N: # weak doublet from new techni-sector)

Technicolor ⇔ SM Higgs

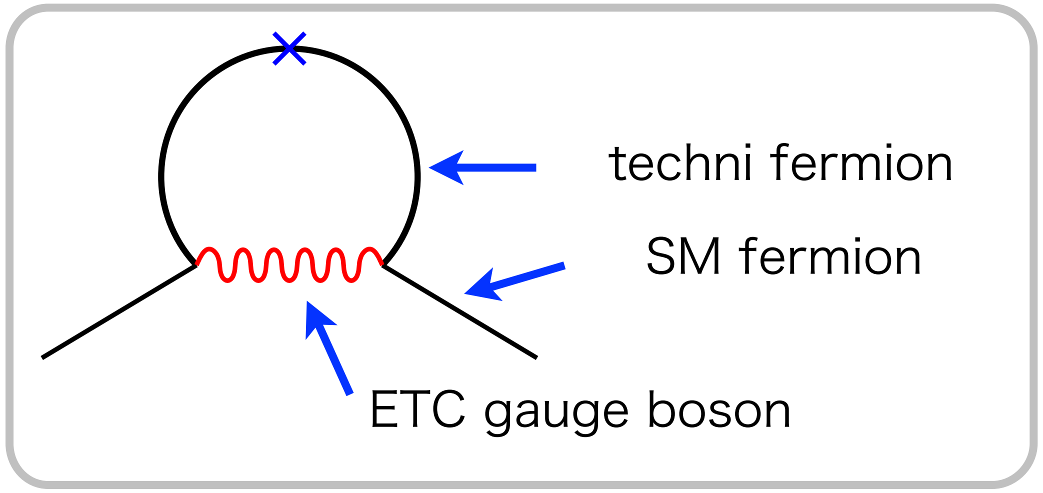
- success of technicolor
  - explaining the origin of EW symmetry breaking
    - dynamics of gauge theory ⇔ $\mu^2 < 0$



  - evading the gauge hierarchy problem: naturalness problem
    - due to logarithmic UV divergence ⇔ power divergence
- fermion masses ?
  - ETC effective 4 Fermi interaction ⇔ fermion-Higgs Yukawa coupling
  - produced by introducing interaction: techni-quarks and SM fermions

Extended Technicolor (ETC)

- fermion masses → extended technicolor (ETC)
- New strong interaction of SU(N_{ETC}): N_{ETC}>N_{TC}, T_{ETC}=(T, f): T∈TC, f∈SM
- SSB: SU(N_{ETC})→SU(N_{TC}) x SM @ Λ_{ETC} ($\gg \Lambda_{TC}$)
- $$\frac{1}{\Lambda_{ETC}^2}\overline{T}T\overline{f}f \to m_f = \frac{\langle \overline{T}T\rangle_{ETC}}{\Lambda_{ETC}^2}$$
- $$\frac{1}{\Lambda_{ETC}^2}\overline{f}f\overline{f}f$$ FCNC



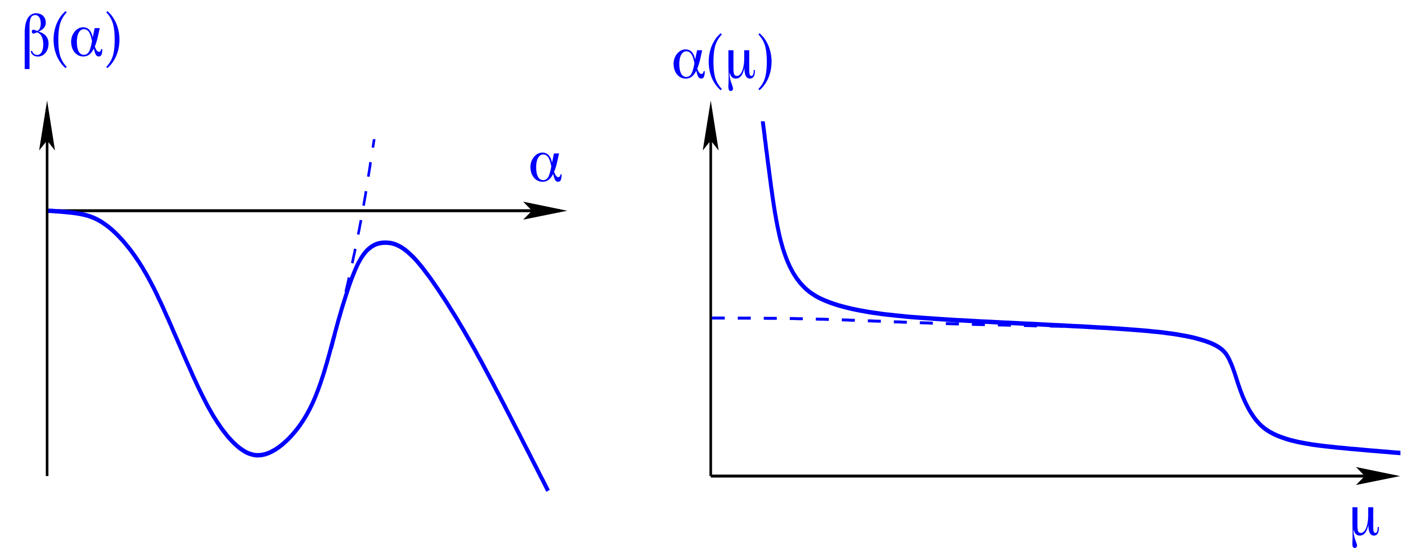
- FCNC should be small ⇔ top or bottom quark mass should be produced

➡ walking TC

Walking Technicolor

- key: to realize suppressed FCNC and appropriate size of fermion masses

[Holdom, Yamawaki-Bando-Matsumoto]



- renormalized gauge coupling
    - to run very slowly (walking)
    - eventually grows at low energies → to produce techni-pions
- mass anomalous dimension
    - large: $\gamma_m \sim 1$

Walking Technicolor

- key: t

Is it possible to construct such a theory ?

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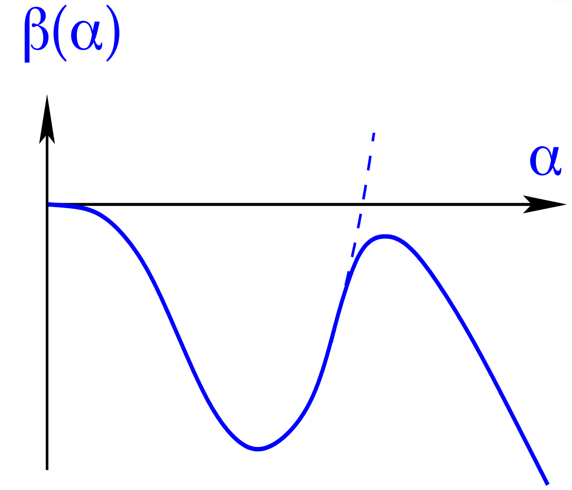

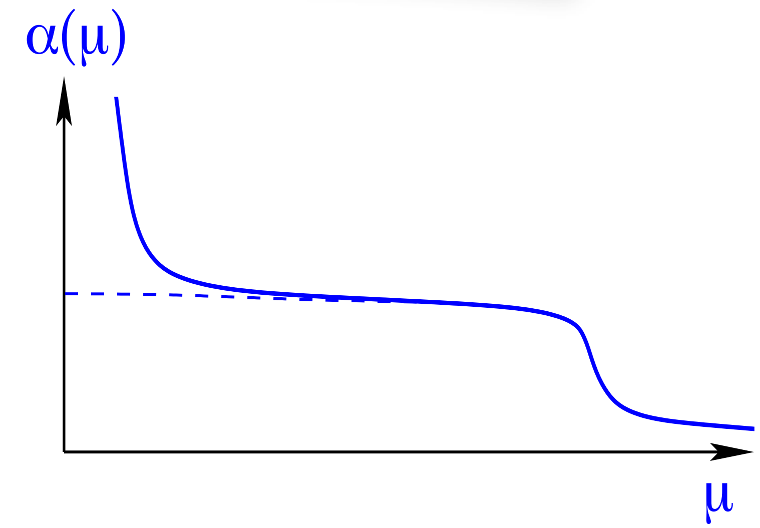

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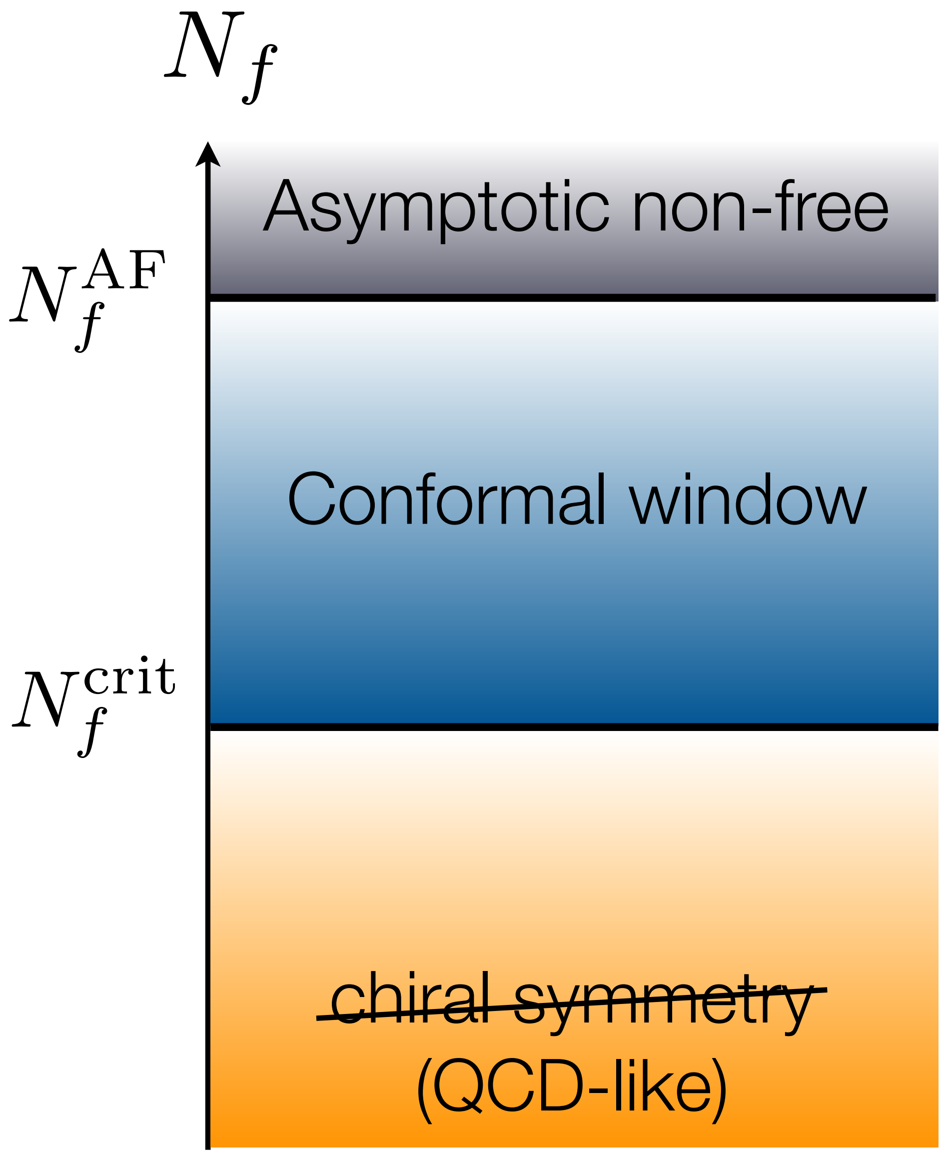
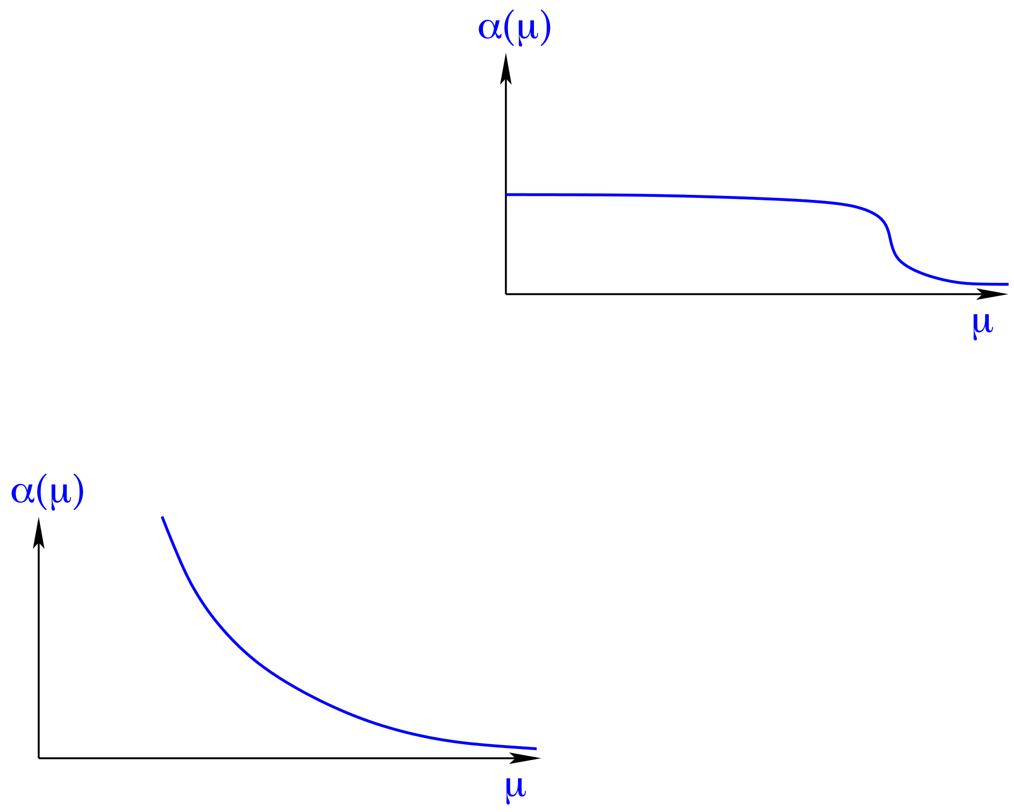
conformal window and walking gauge coupling

- non-Abelian gauge theory with N_f *massless* fermions -





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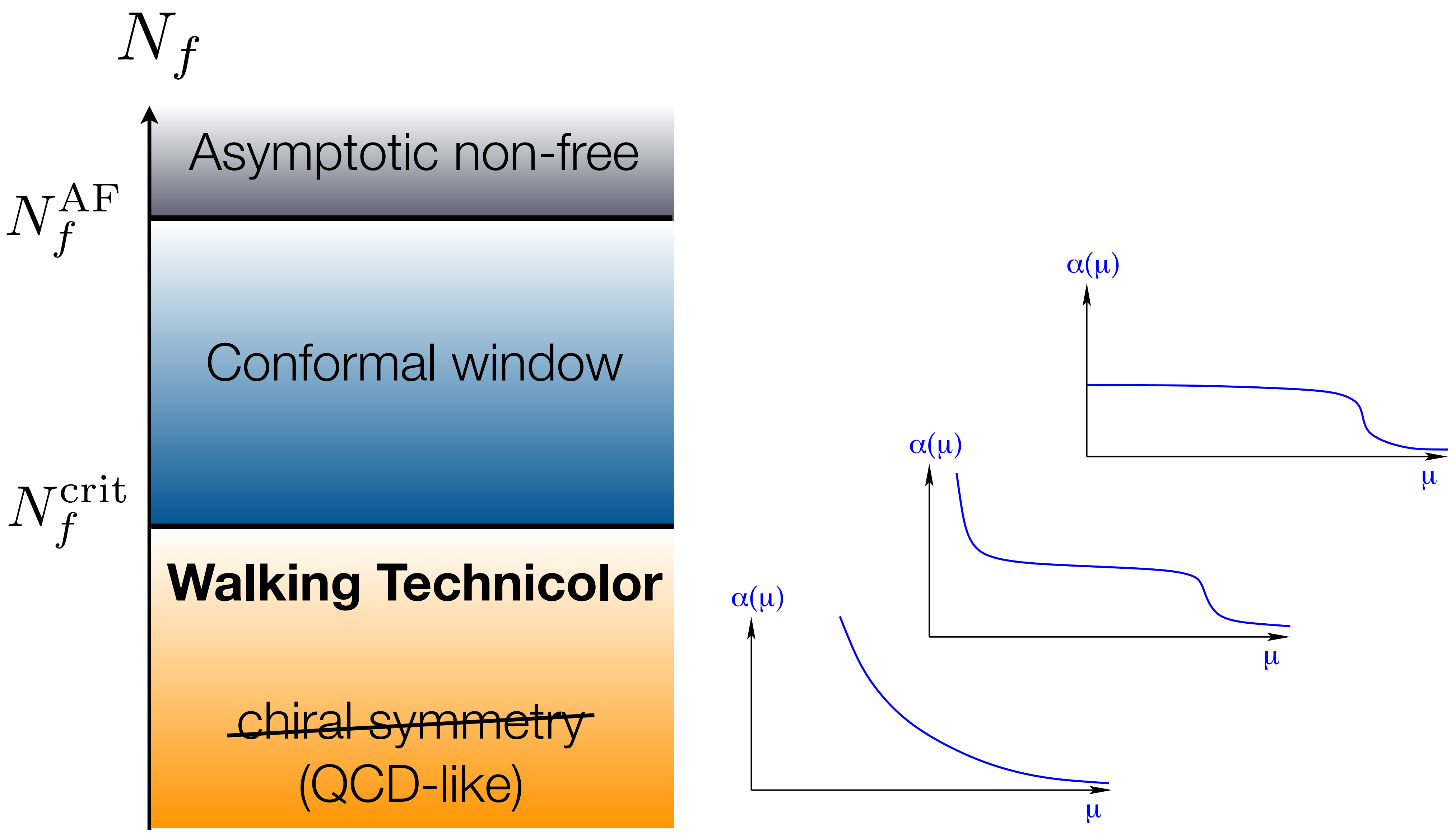

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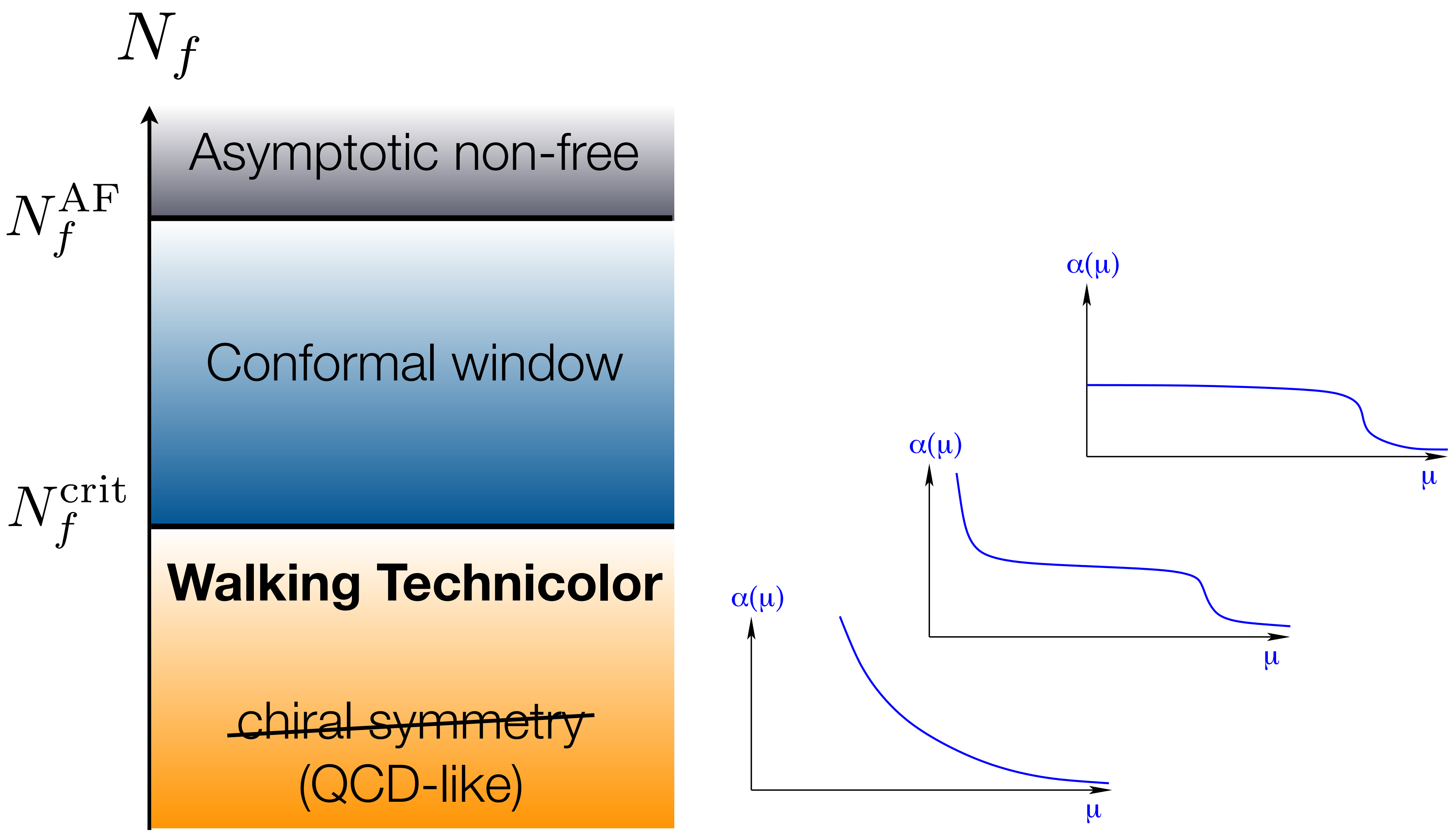

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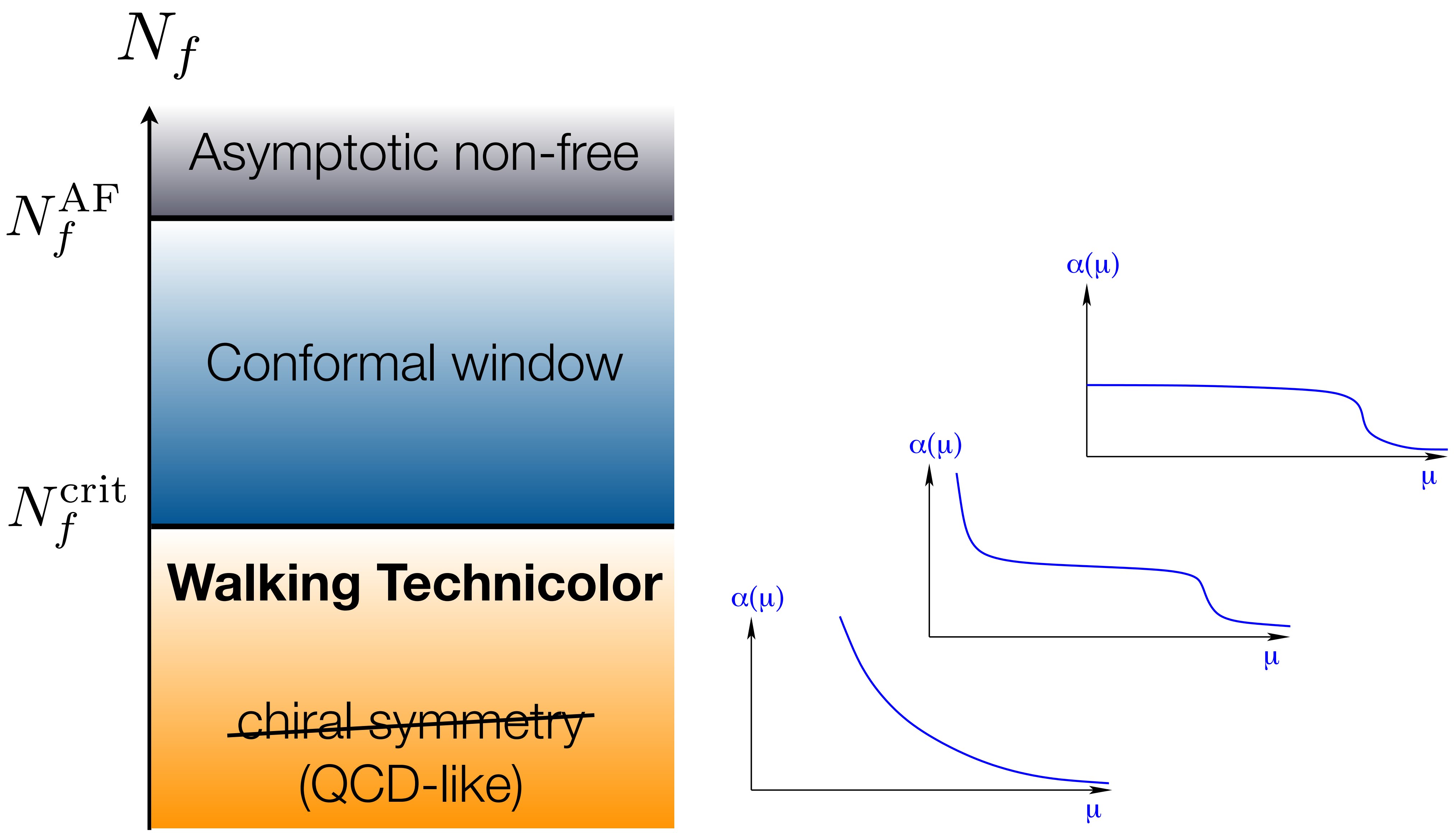

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conformal window and walking gauge coupling

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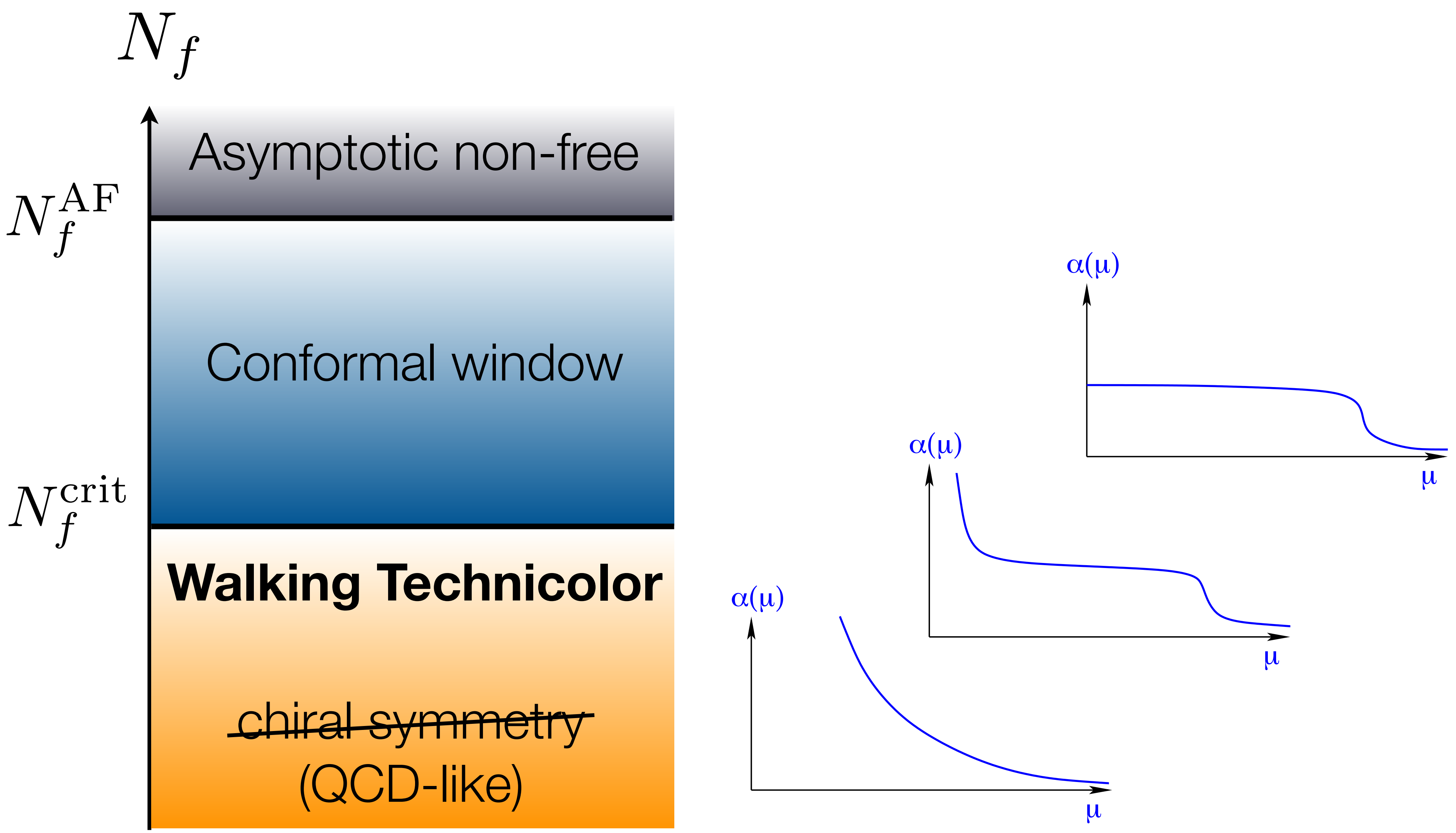
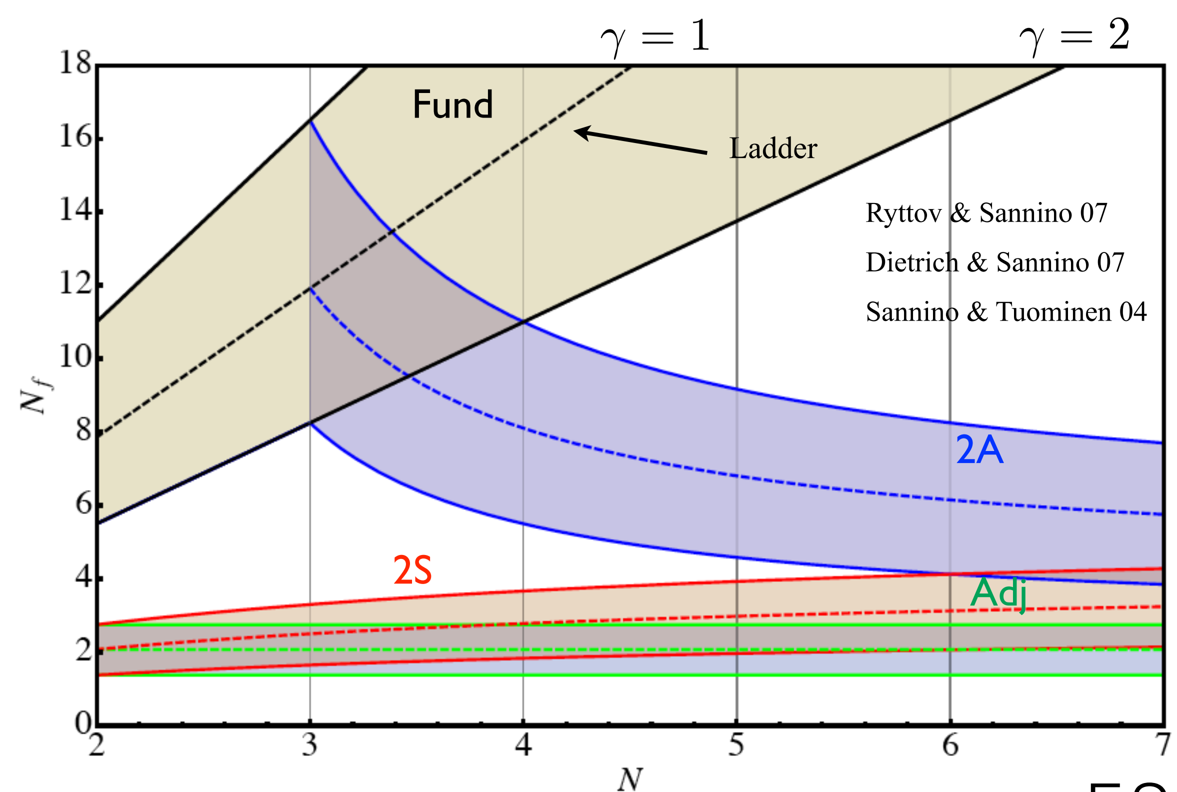


- Walking Techinicolor could be realized just below the conformal window
- crucial information: $N_f^{\rm crit}$ and...
- mass anomalous dimension γ & the composite mass spectrum around $N_f^{\rm crit}$

models being studied:

- SU(3)
  - fundamental: Nf=6, 8, 10, 12, 16
  - sextet: Nf=2
- SU(2)
  - adjoint: Nf=2
  - fundamental: Nf=8
- SU(4)
  - decuplet: Nf=2

SU(N) Phase Diagram



F.Sannino

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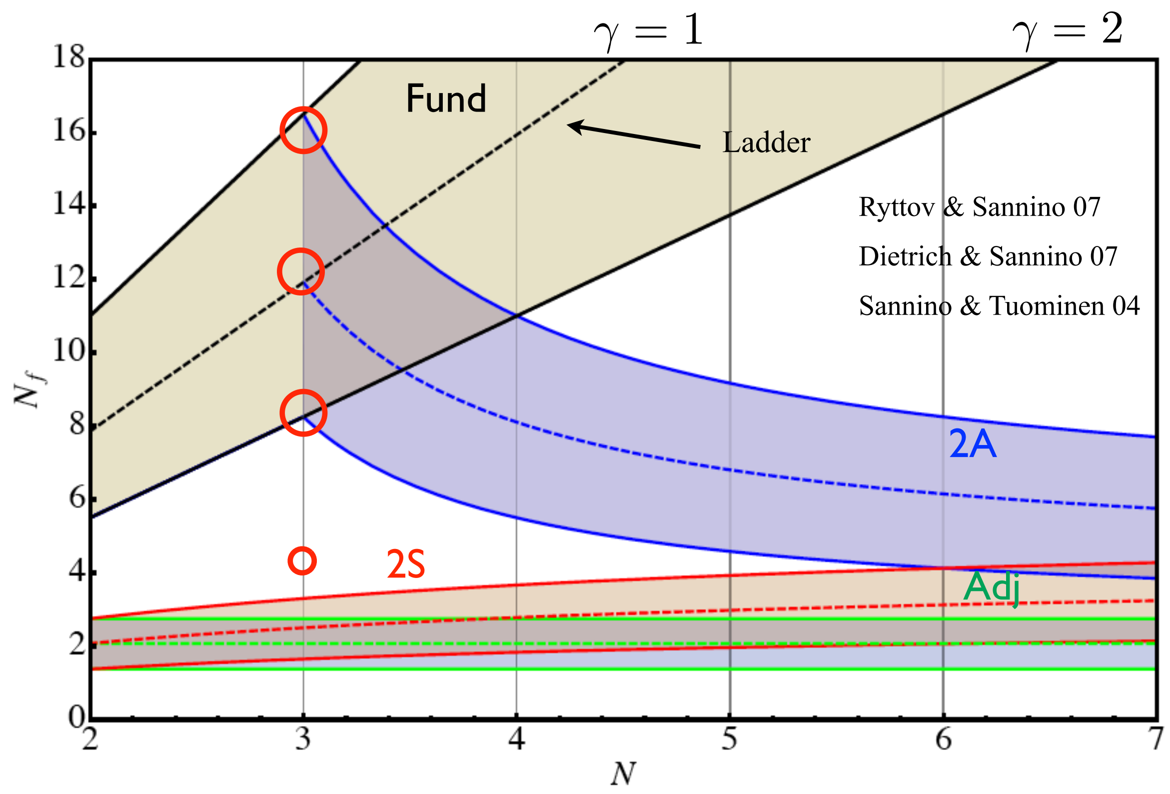

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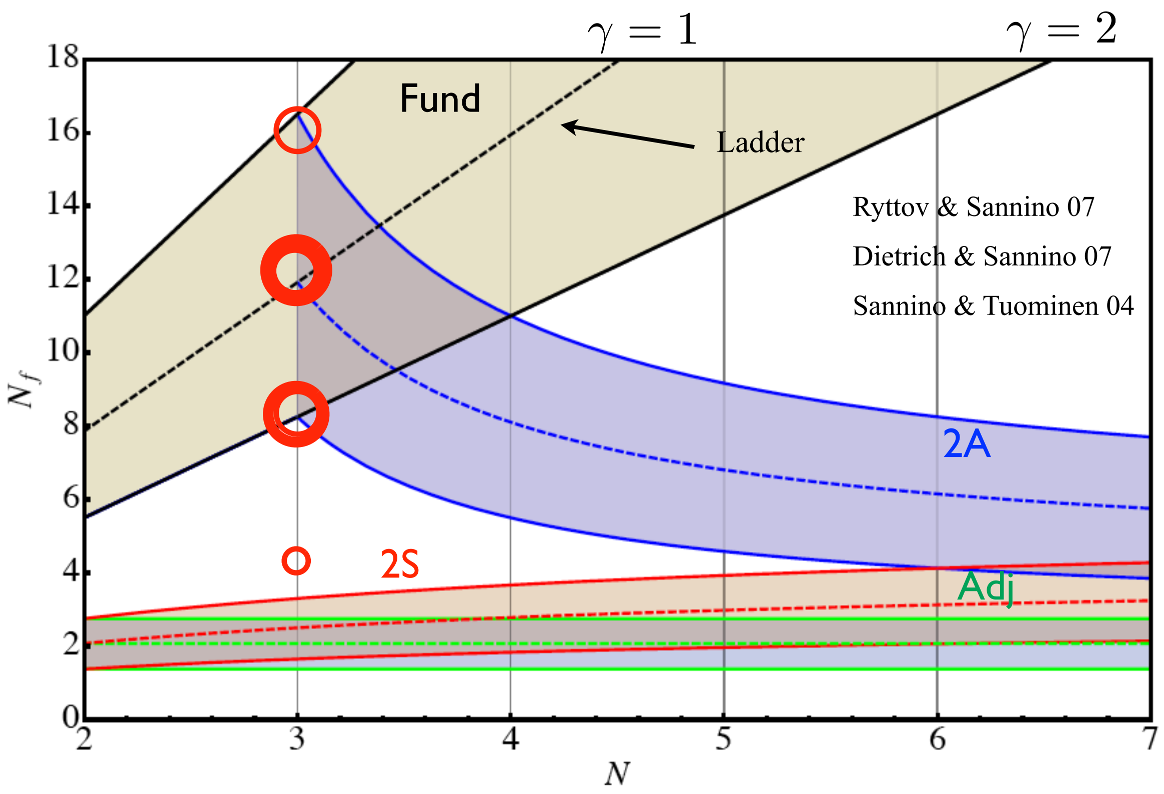
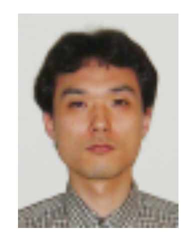


LatKMI collaboration

- YA, T.Aoyama, M.Kurachi, T.Maskawa, K.Miura, K.Nagai,

H.Ohki, K.Yamawaki, T.Yamazaki

名古屋大学    KMI

- E. Rinaldi

Lawrence Livermore National Laboratory

A.Shibata

KEK

LatKMI mission

- find / understand (near) **conformal dynamics** in gauge theory: late 2010
    - using a state-of-the-art lattice discretization (HISQ) and computation
- find **conformal window** in SU(3) gauge theory w. **N_f** m=0 fundamental fermions
- find a **walking technicolor theory** in SU(3) gauge theory
- investigate **N_f=8** in some detail
- investigate **flavor singlet scalar** in SU(3) gauge theory
- test N_f=8 against experiment

LatKMI publications

- LatKMI, PRD 85 (2012), “Study of the conformal hyperscaling relation through the Schwinger-Dyson equation” [non-lattice]
- LatKMI, PRD 86 (2012), “Lattice study of conformality in twelve-flavor QCD”
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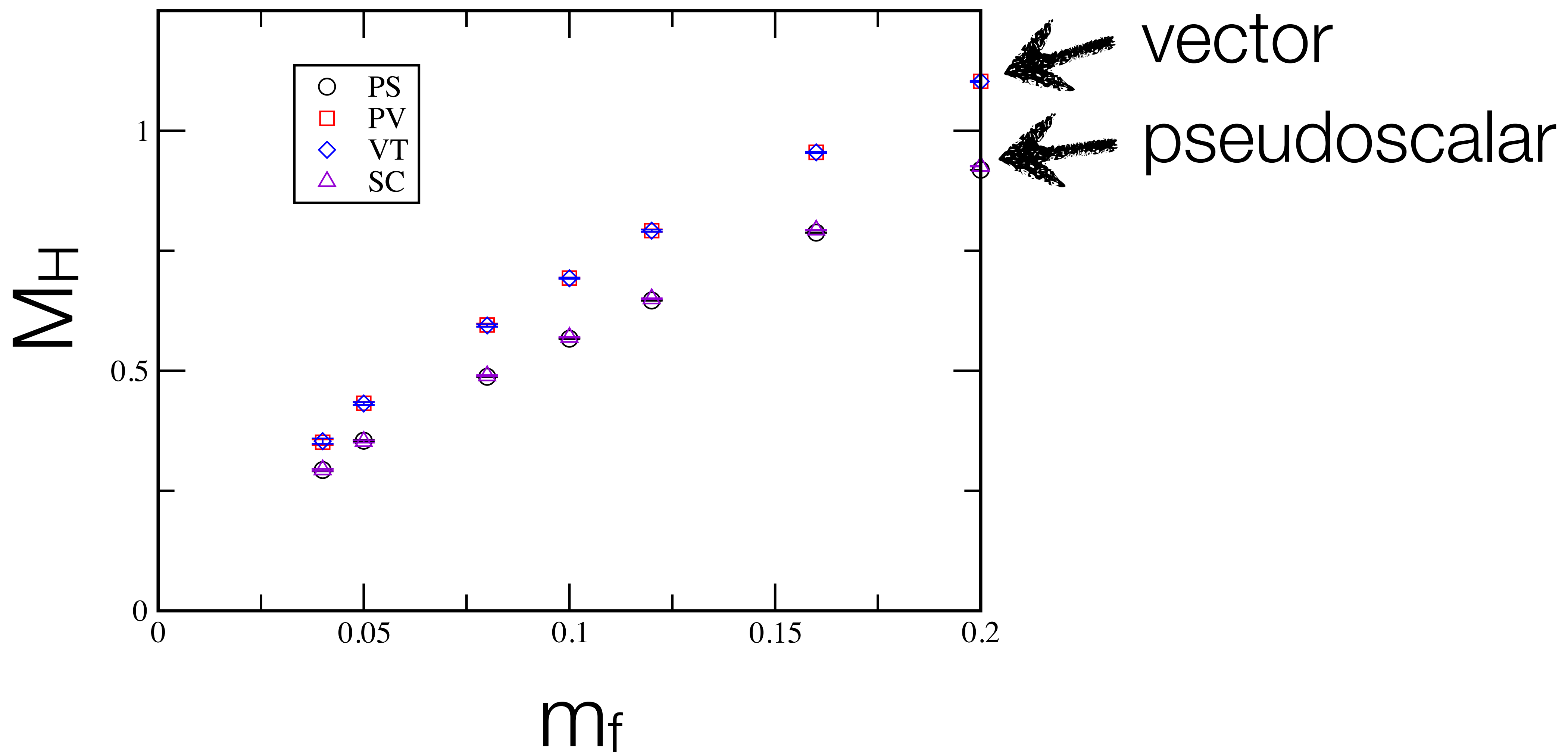
Simulation

- Fermion Formulation: HISQ (Highly Improved Staggered Quarks)
  - being used for state-of-the-art QCD calculations / MILC,..
- Gauge Field Formulation:tree level Symanzik gauge
- $N_f=4$: $\beta=6/g^2=3.7$, $V=L^3 xT$: $L/T=2/3$; $L=12, 16$
- $N_f=8$: $\beta=6/g^2=3.8$, $V=L^3 xT$: $L/T=3/4$; $L=18, 24, 30, 36$
- $N_f=12$ (two lattice spacings):
  - $\beta=6/g^2=3.7$, $V=L^3 xT$: $L/T=3/4$; $L=18, 24, 30$, $0.04 \leqq m_f \leqq 0.2$
  - $\beta=6/g^2=4.0$, $V=L^3 xT$: $L/T=3/4$; $L=18, 24, 30$, $0.05 \leqq m_f \leqq 0.24$
- using MILC code v7, with modification: HMC and speed up in MD

staggered flavor symmetry for N_f=12 HISQ

- comparing masses with different staggered operators for π & ρ for β=3.7



- excellent staggered flavor symmetry, thanks to HISQ

Hadron spectrum:
m_f-response in mass deformed theory

- IR conformal phase:
  - coupling runs for $\mu < m_f$: like $n_f=0$ QCD with $\Lambda_{QCD} \sim m_f$
  - multi particle state : $M_H \propto m_f^{1/(1+\gamma_m^*)}$; $F_\pi \propto m_f^{1/(1+\gamma_m^*)}$ (criticality @ IRFP)
- SχSB phase:
  - ChPT
  - at leading: $M_\pi^2 \propto m_f$, ; $F_\pi = F + c\, m_f$

a crude study using ratios

- conformal scenario:
  - $M_H \propto m_f^{1/(1+\gamma_m^*)}$; $F_\pi \propto m_f^{1/(1+\gamma_m^*)}$ for small m_f

★ $F_\pi/M_\pi \to$ const. for small m_f

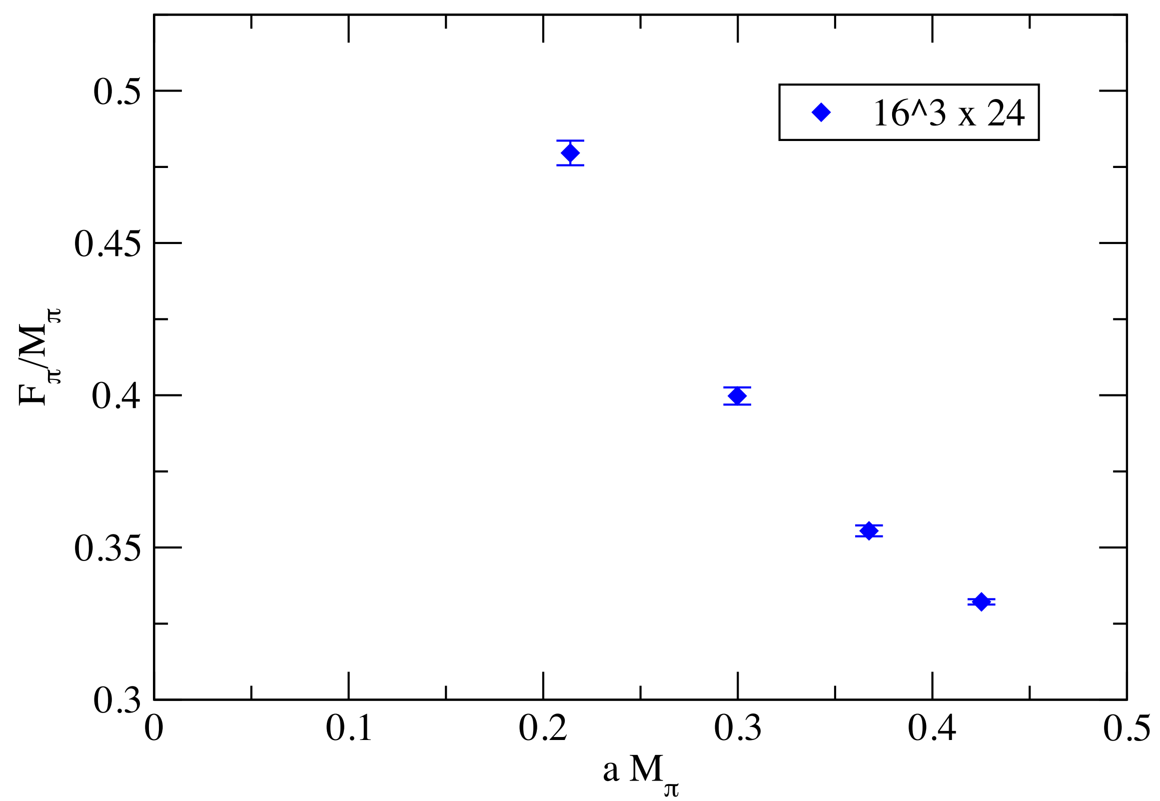
★ $M_\rho/M_\pi \to$ const. for small m_f

- chiral symmetry breaking scenario:
  - $M_\pi^2 \propto m_f$, ; $F_\pi = F + c' M_\pi^2$ for small m_f

★ $F_\pi/M_\pi \to \infty$ for $m_f \to 0$

a crude analysis: F_π/M_π vs M_π

N_f=4



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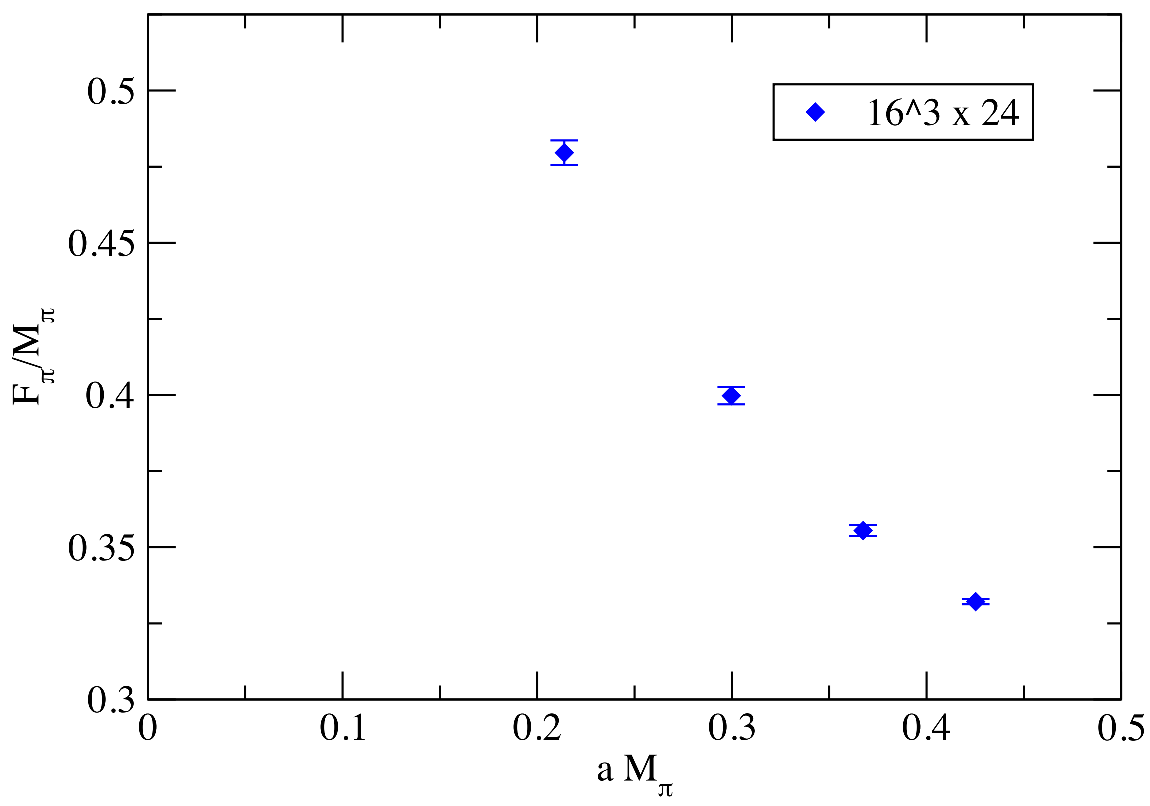

- tends to diverge towards the chiral limit ($M_\pi \to 0$)

a crude analysis: F_π/M_π vs M_π

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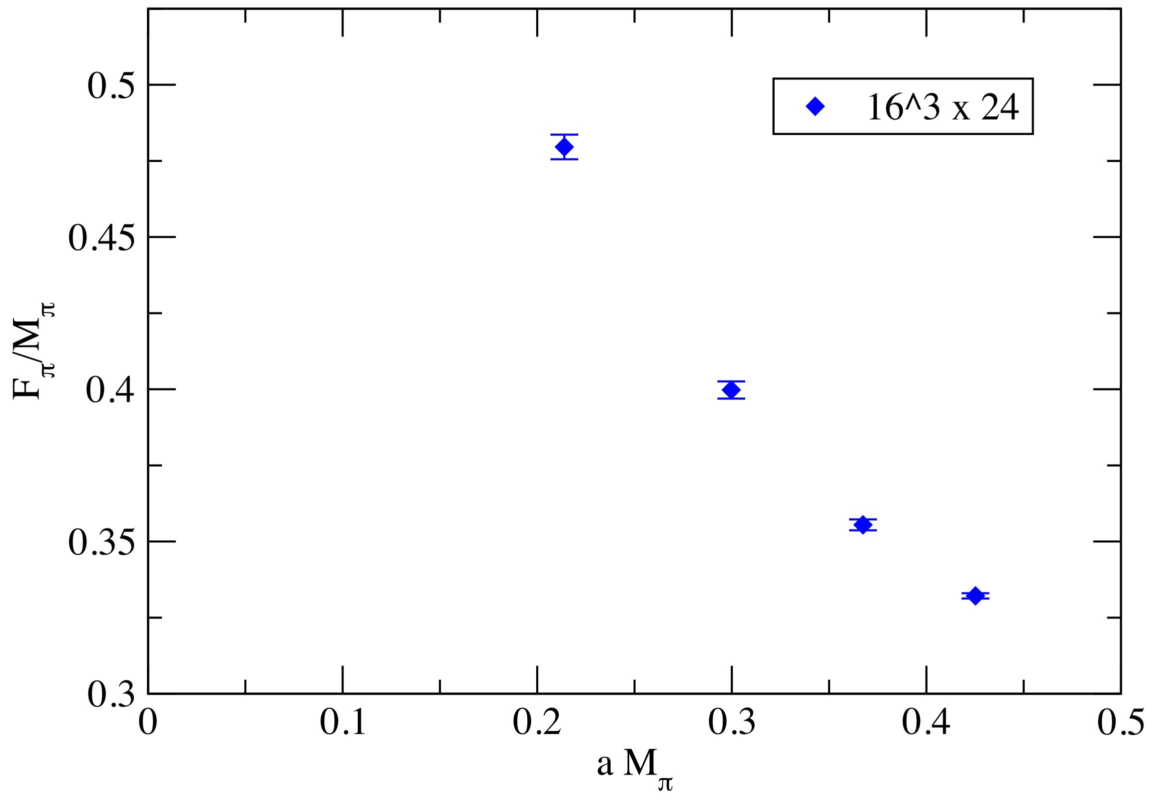
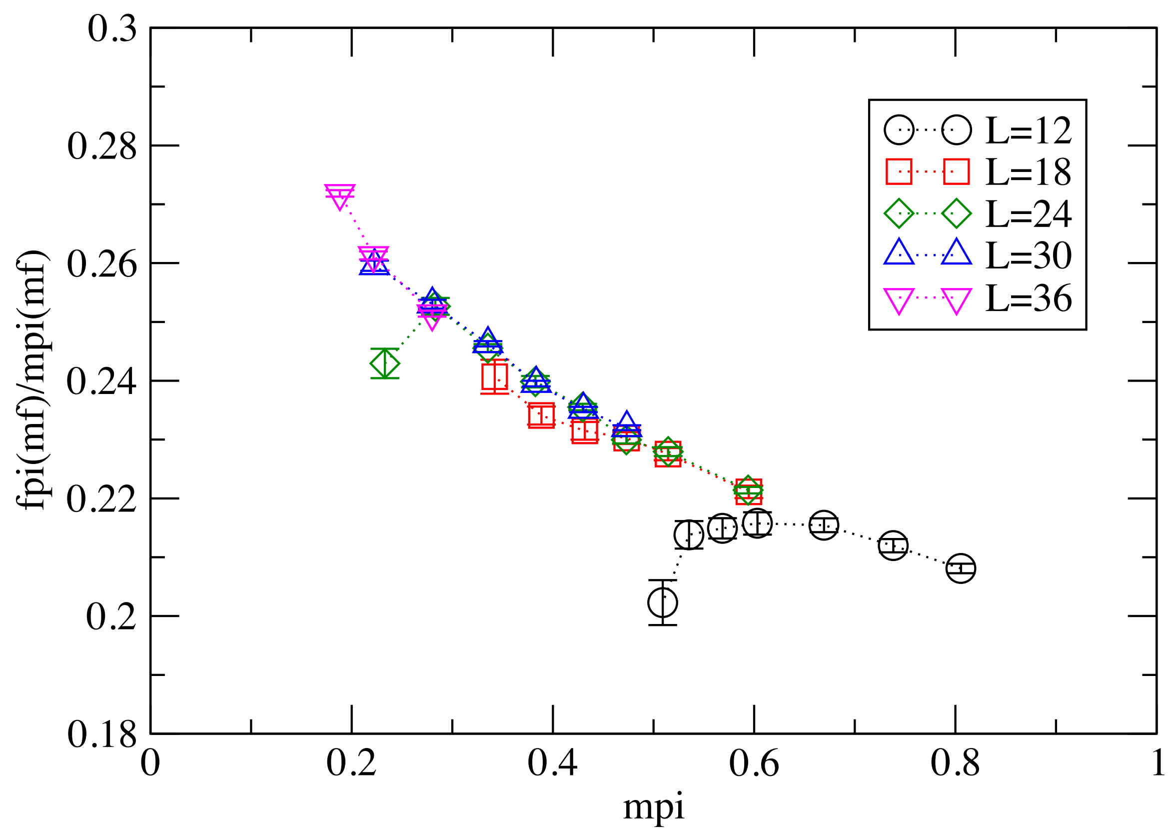


- tends to diverge towards the chiral limit ($M_\pi \to 0$)
- spontaneous chiral symmetry breaking

a crude analysis: F_π/M_π vs M_π

N_f=8



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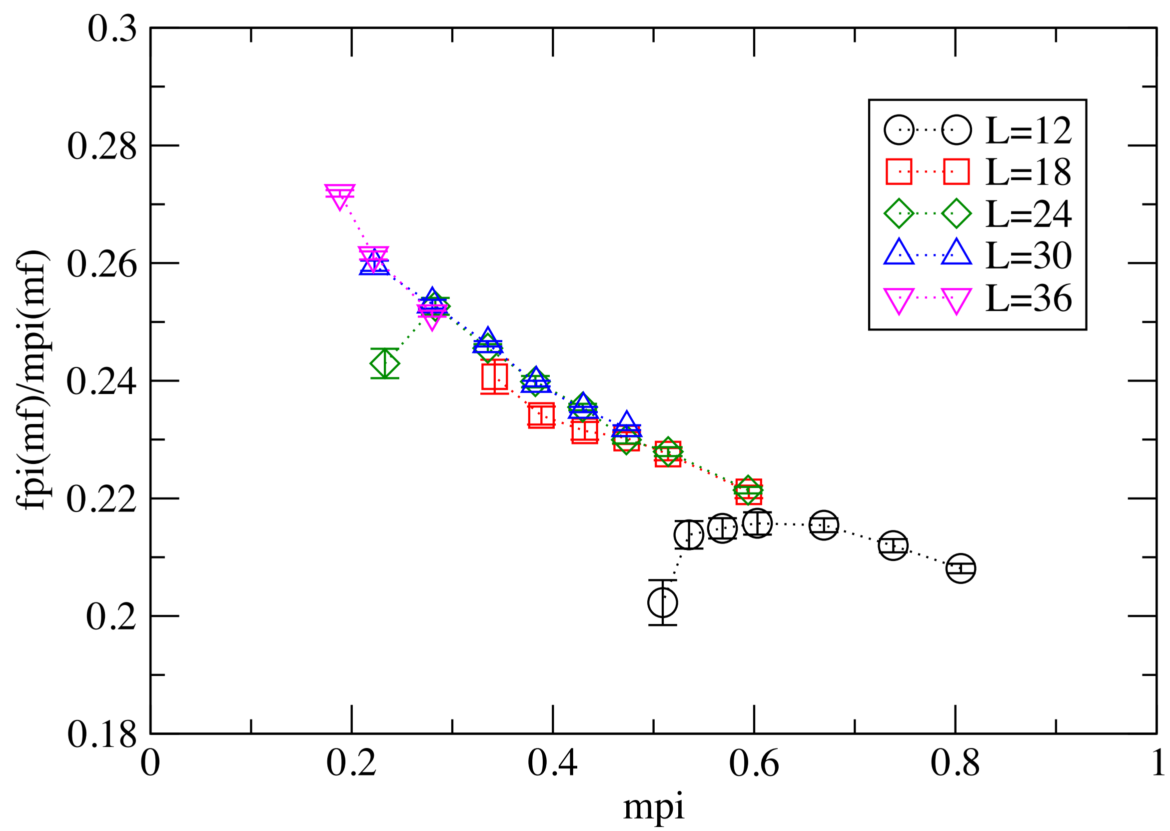

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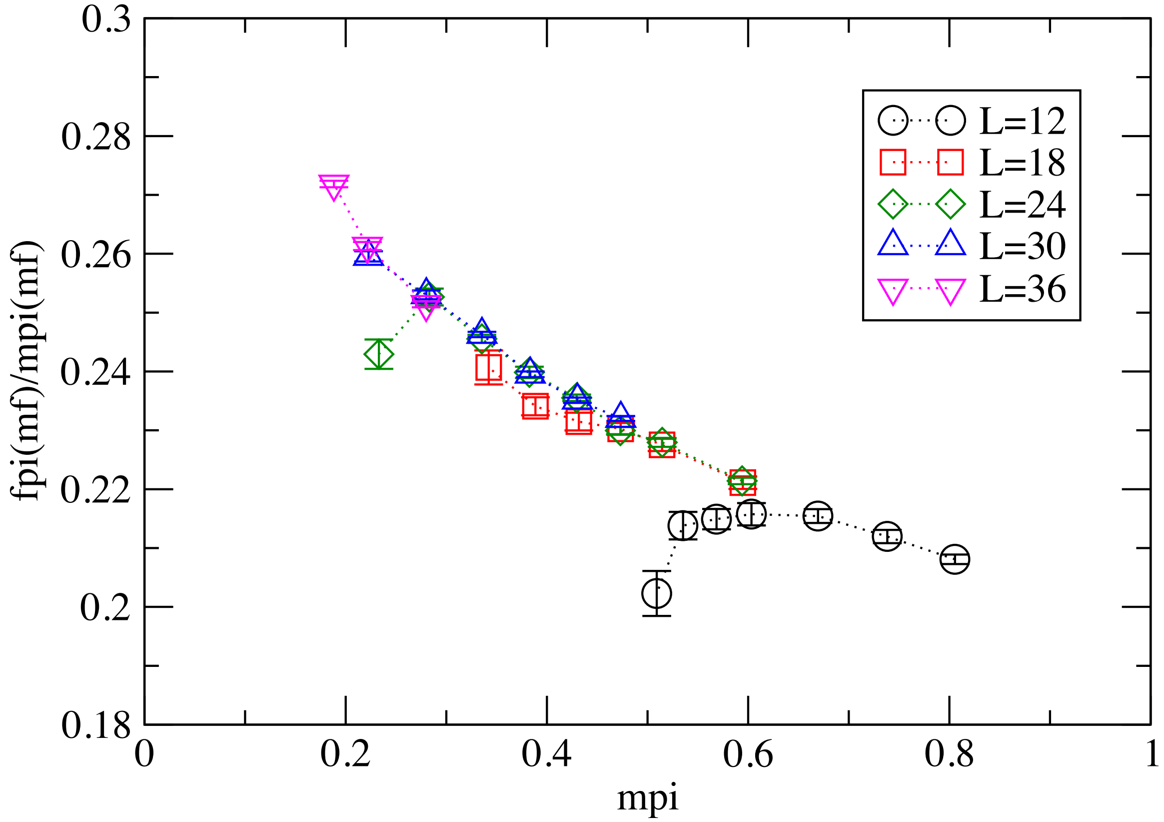
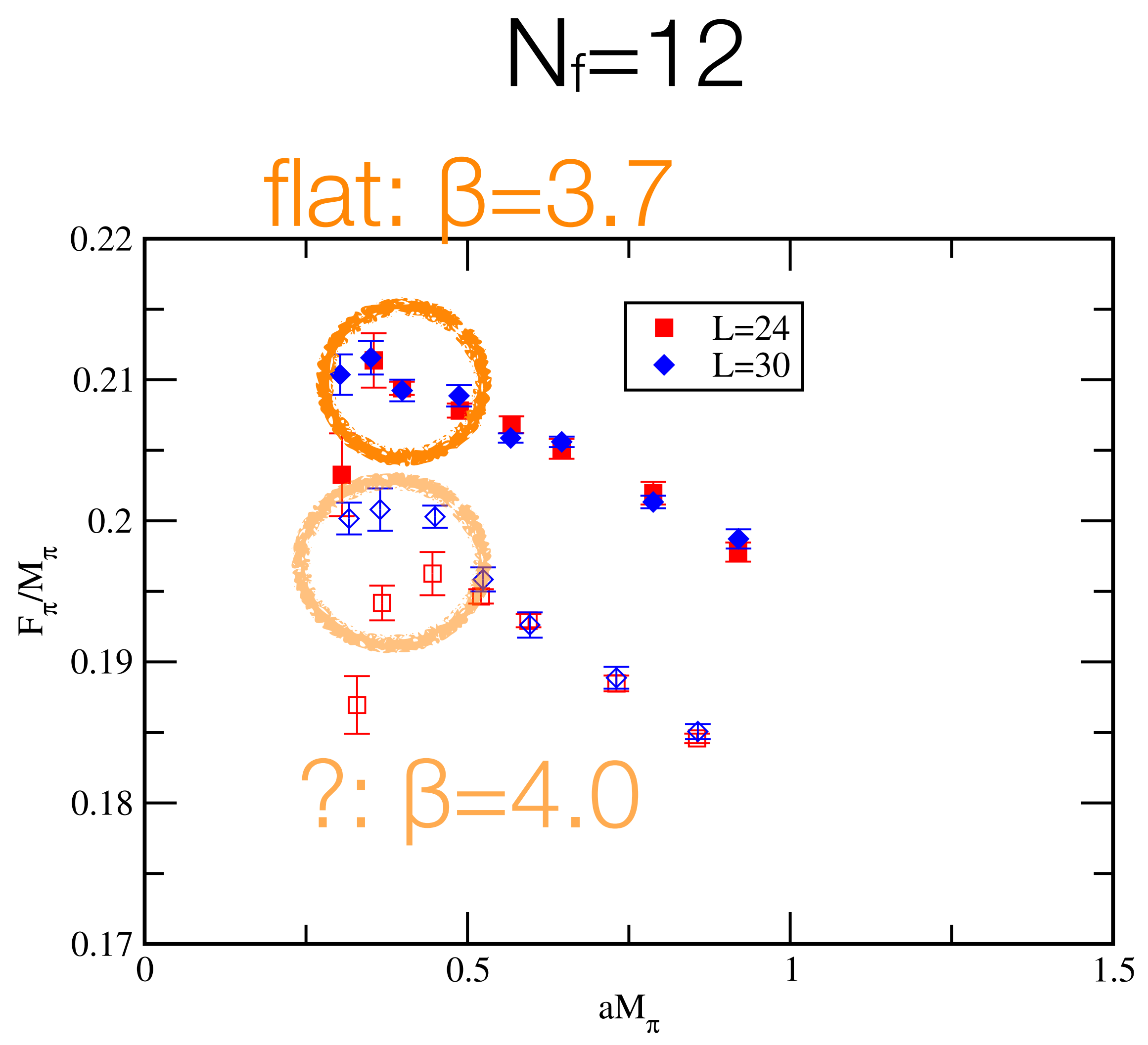


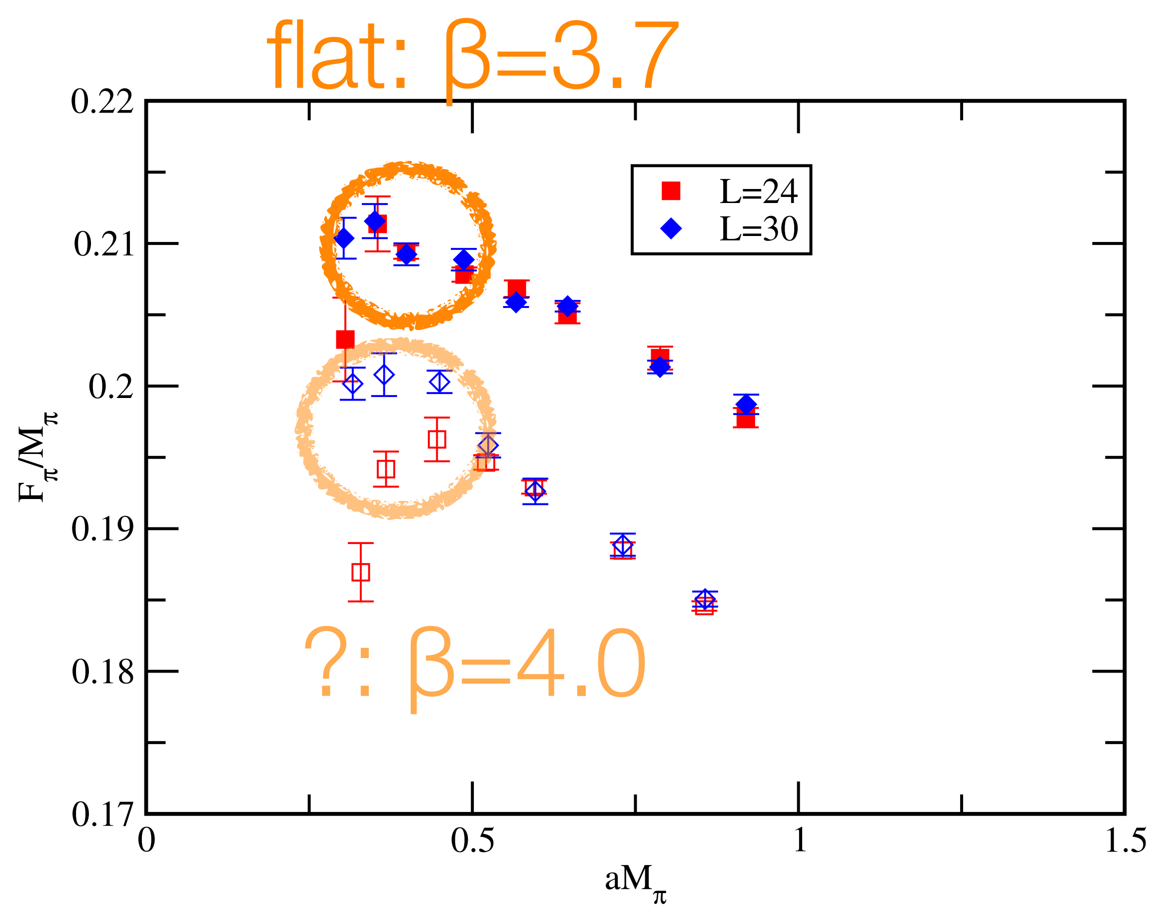
- tends to diverge towards the chiral limit ($M_\pi \to 0$)
- spontaneous chiral symmetry breaking, likely

a crude analysis: F_π/M_π vs M_π



a crude analysis: F_π/M_π vs M_π

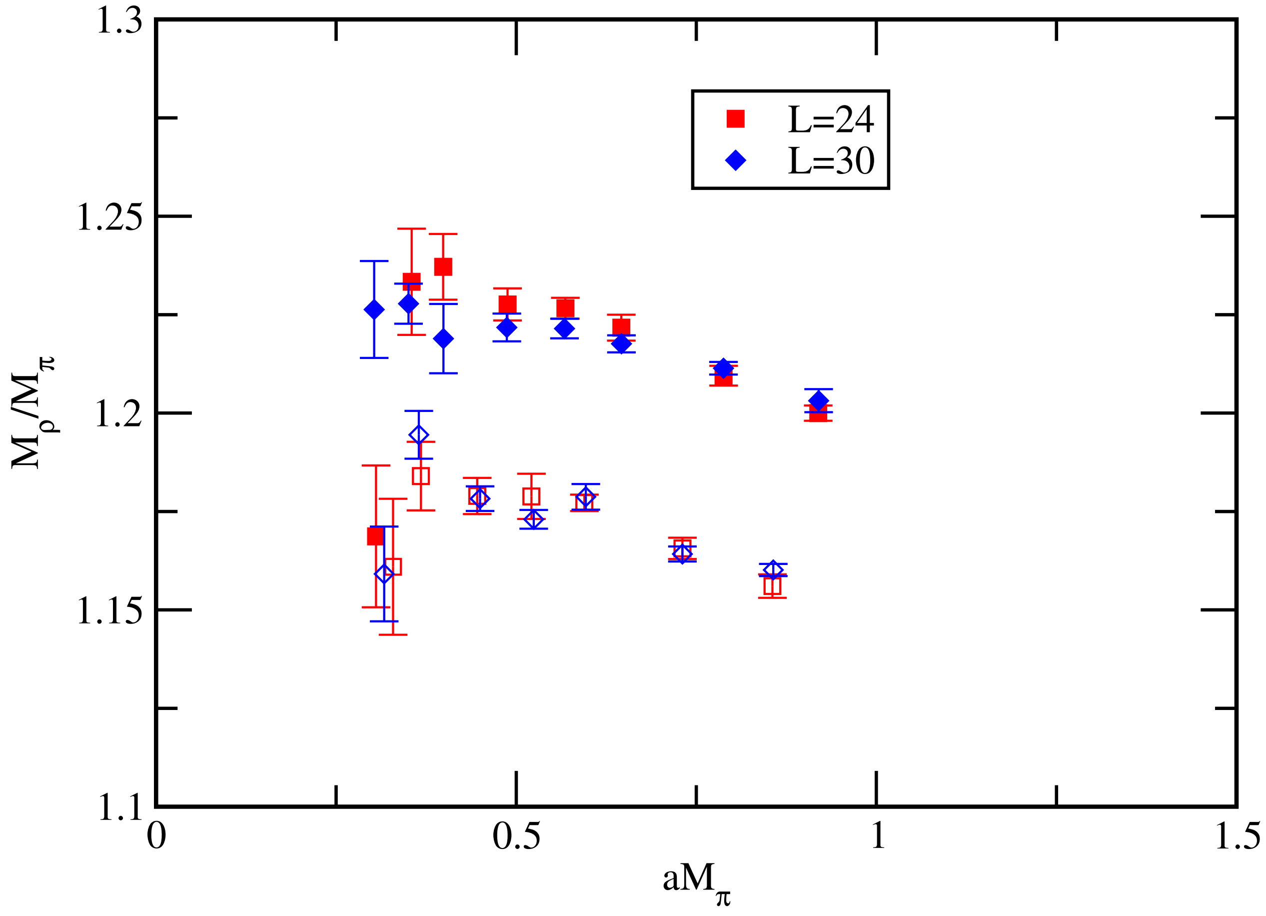
N_f=12



- β=3.7: small mass: consistent with conformal scenario
- β=4.0: volume likely to small to discuss the scaling

a crude analysis: M_ρ/M_π vs M_π

N_f=12: HISQ



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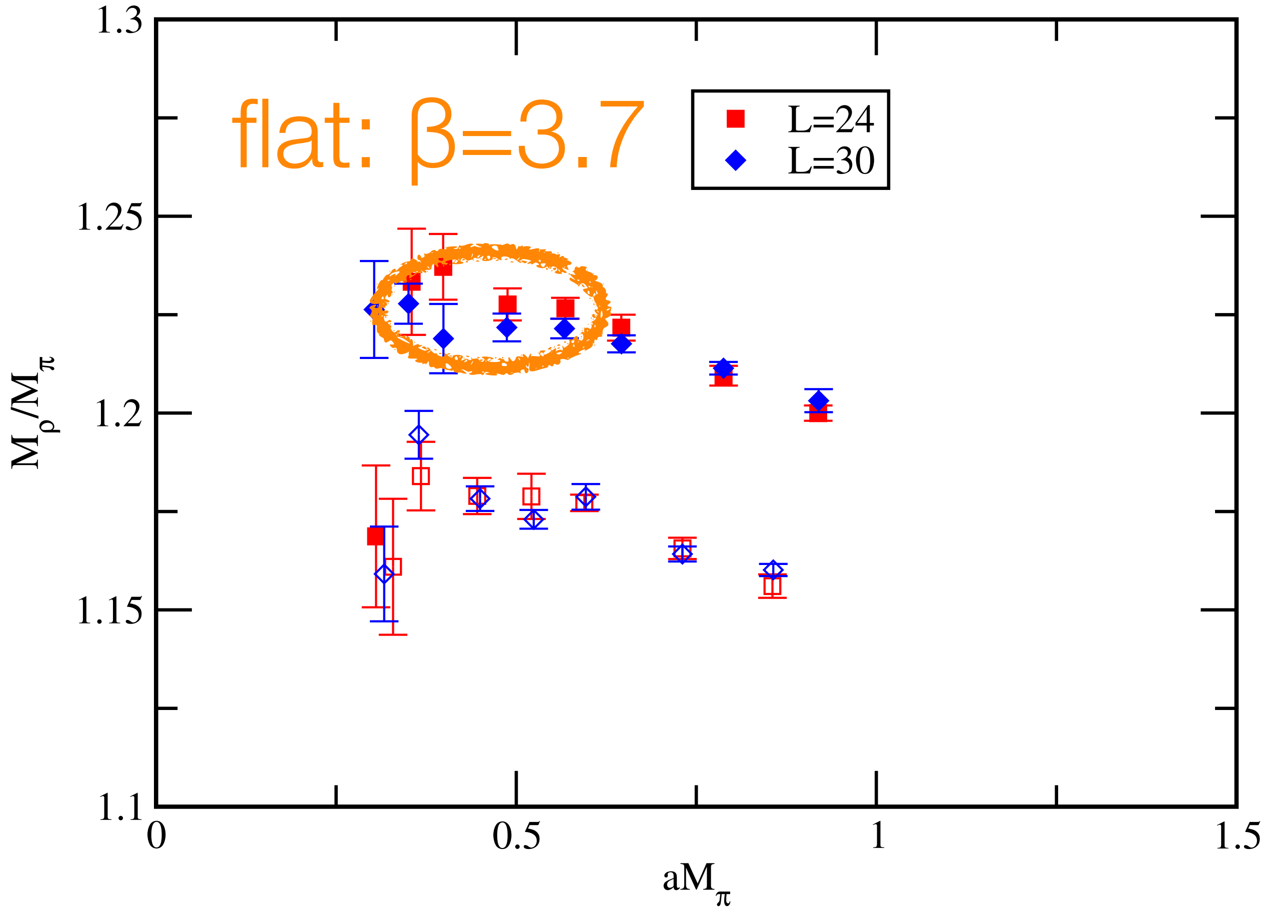

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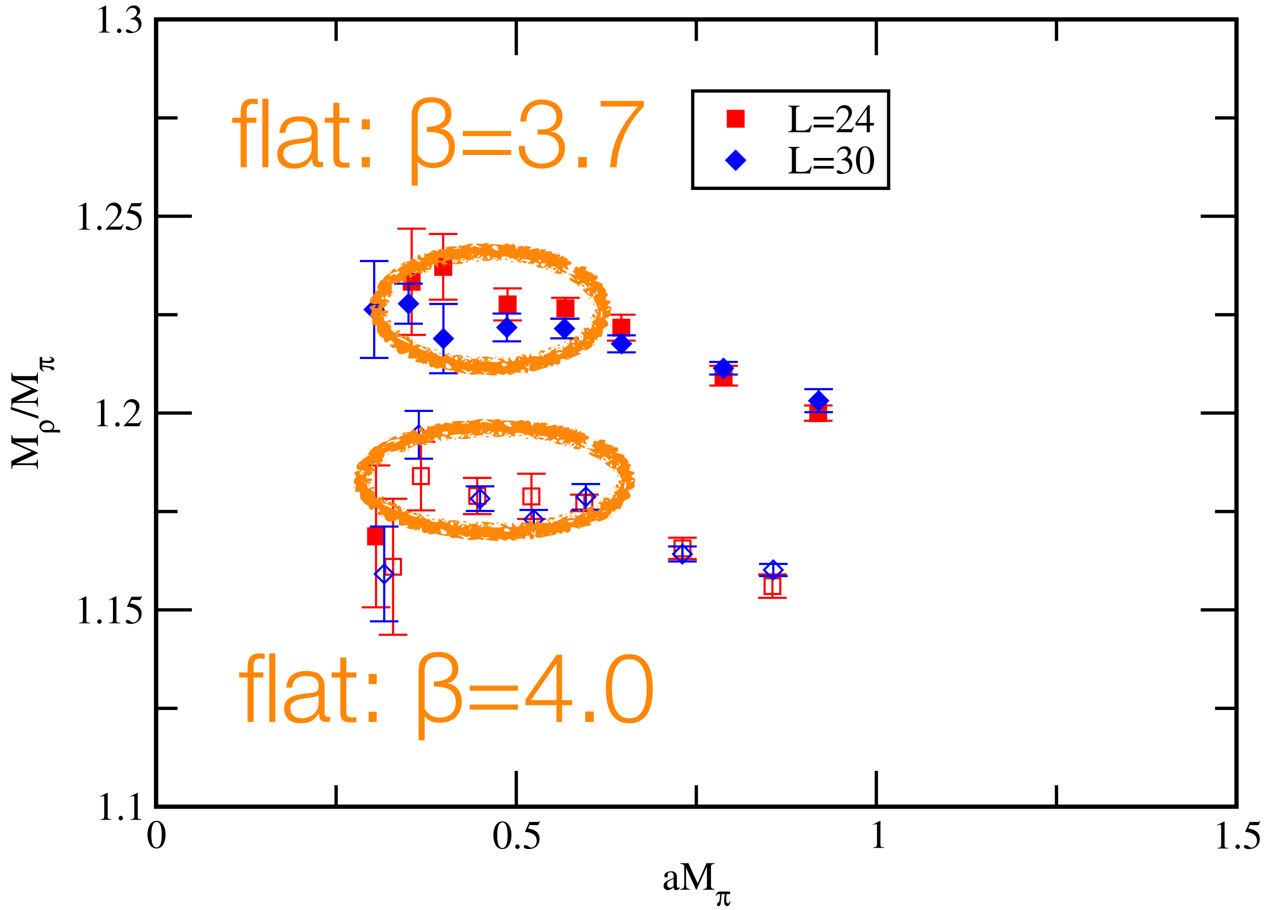

- β=3.7 & 4.0: small mass (wider than F_π): consistent with hyper scaling (HS)

a crude analysis: M_ρ/M_π vs M_π

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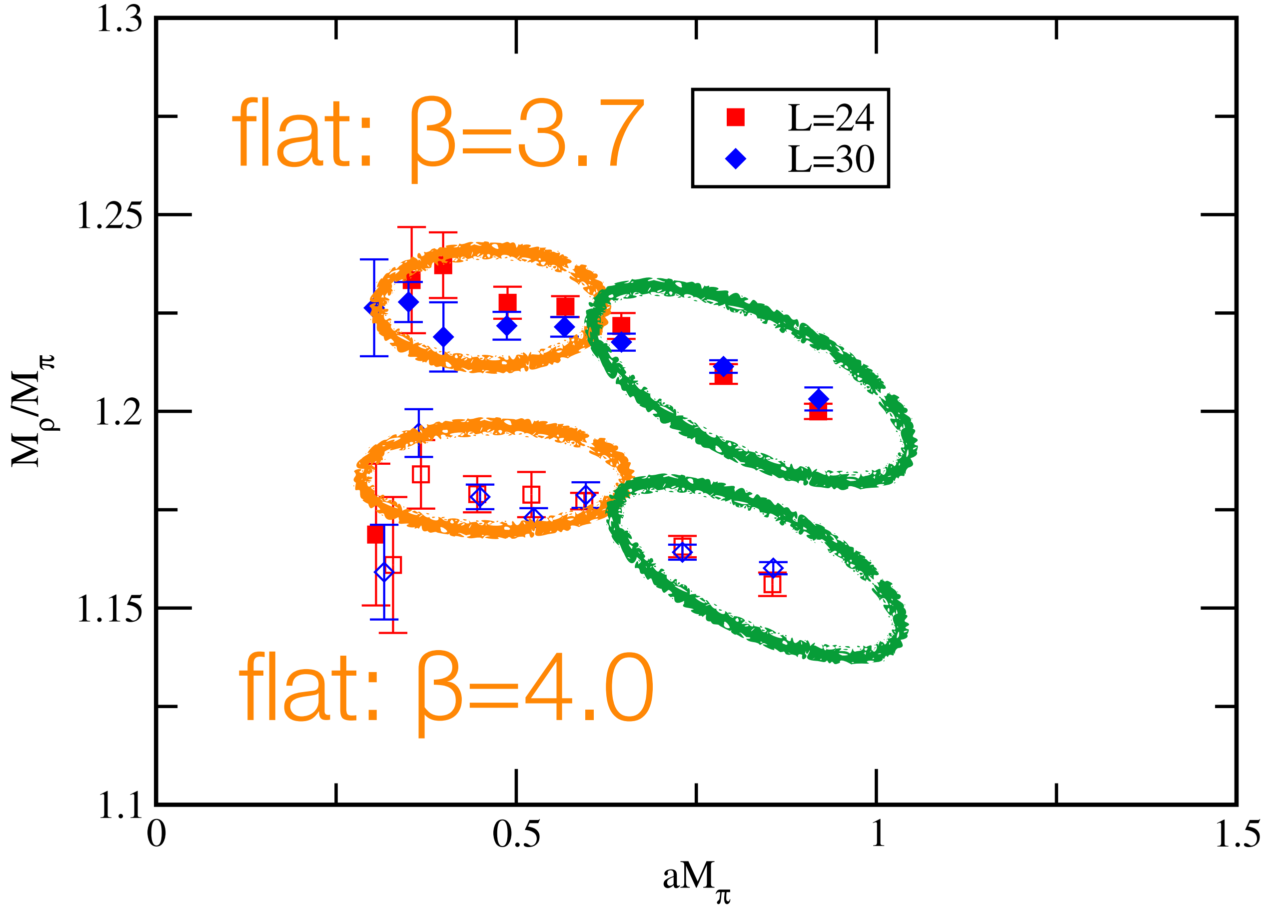

- β=3.7 & 4.0: small mass (wider than F_π): consistent with hyper scaling (HS)
- mass dependence at the tail is due to non-universal mass correction to HS

a crude analysis: M_ρ/M_π vs M_π

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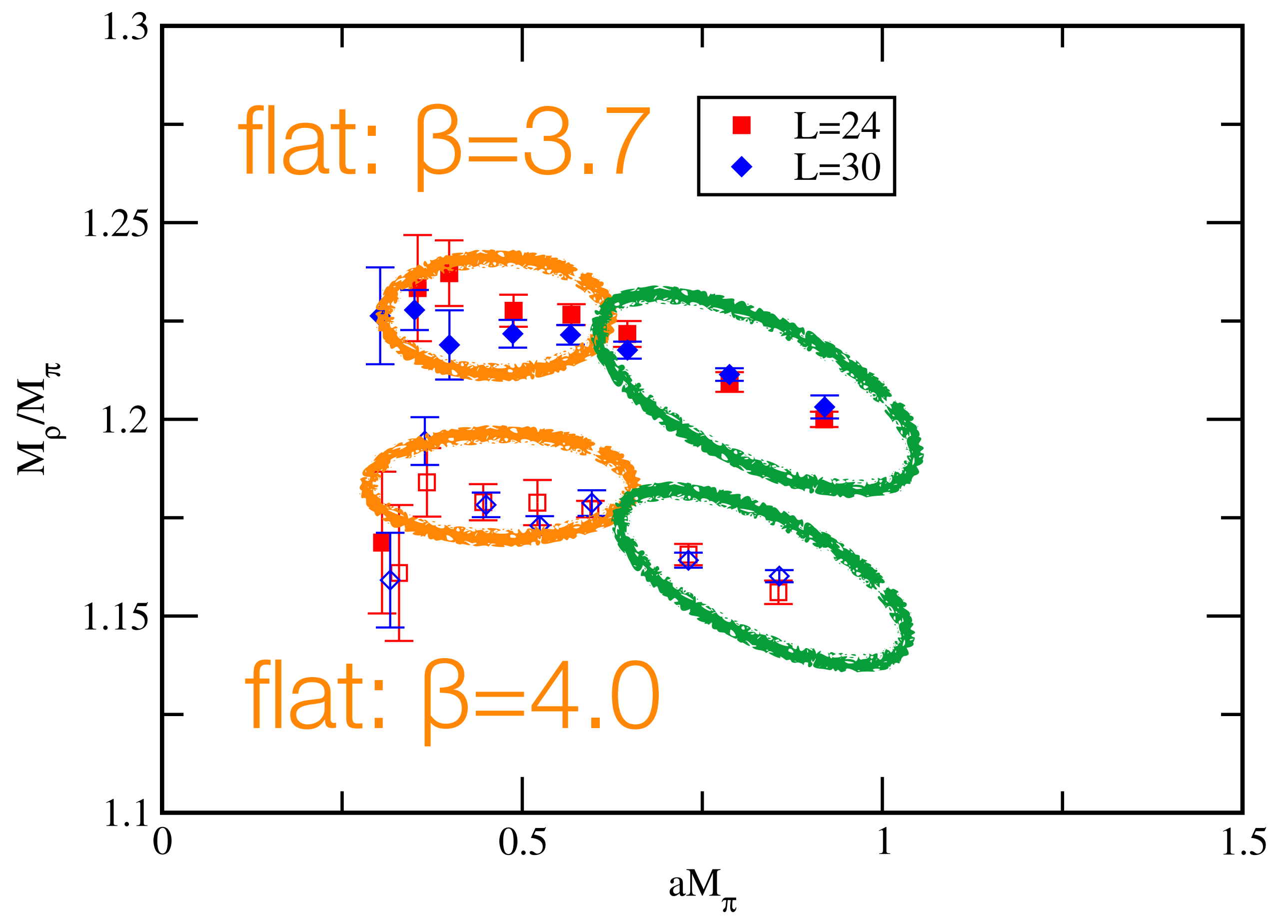

- one may attempt to perform a matching

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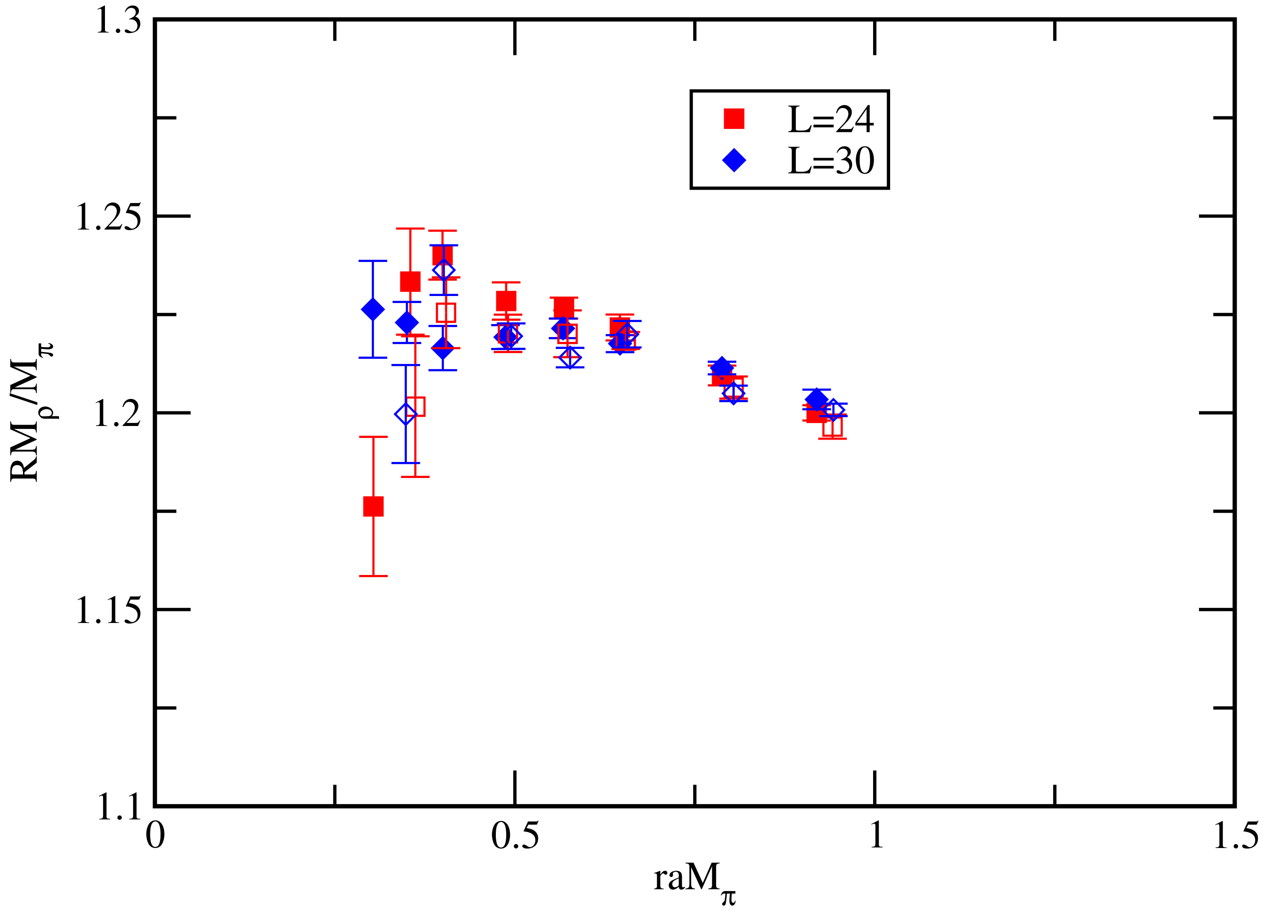

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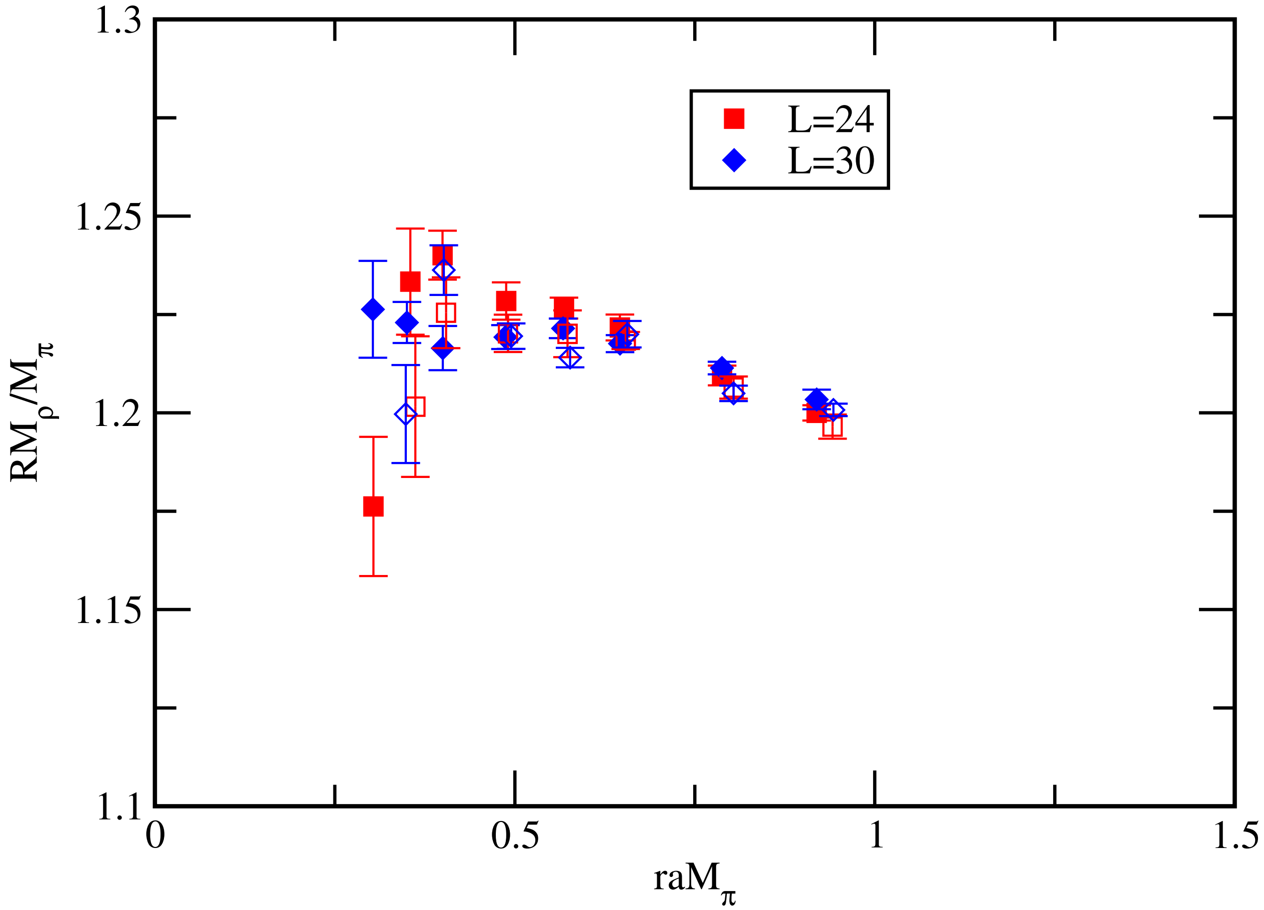

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➡ a(β=3.7) / a(β=4.0) > 1

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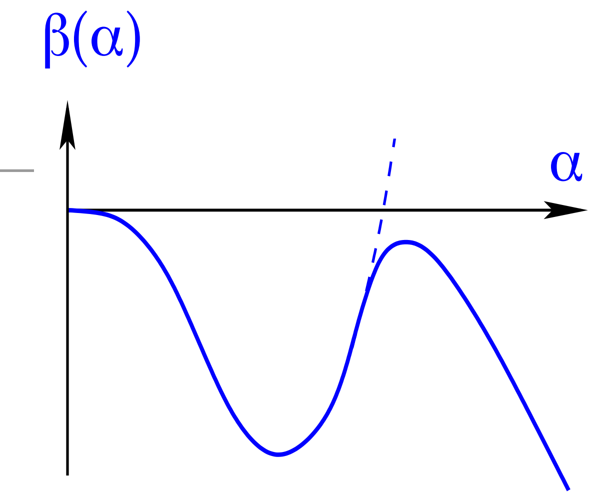

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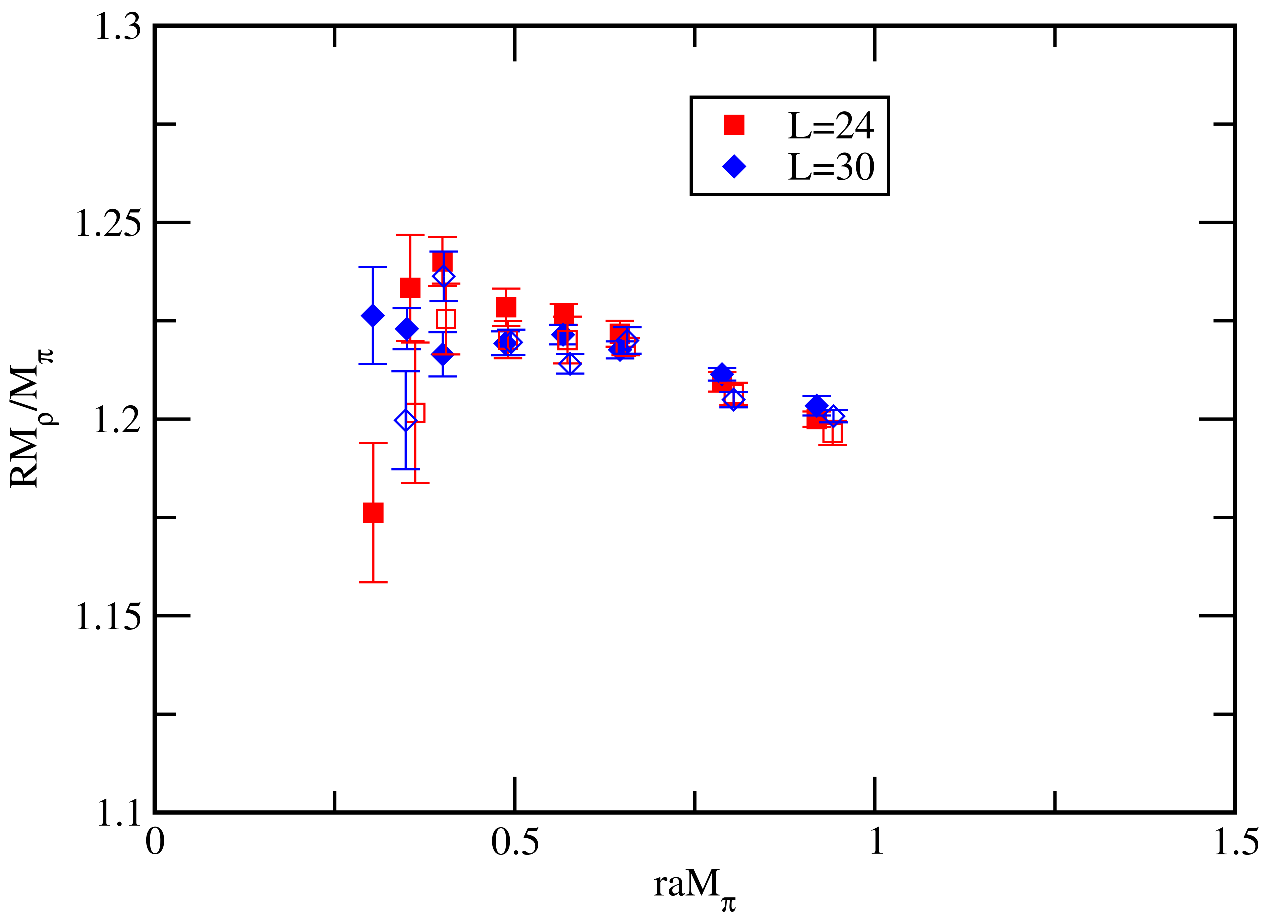


- one may attempt to perform a matching

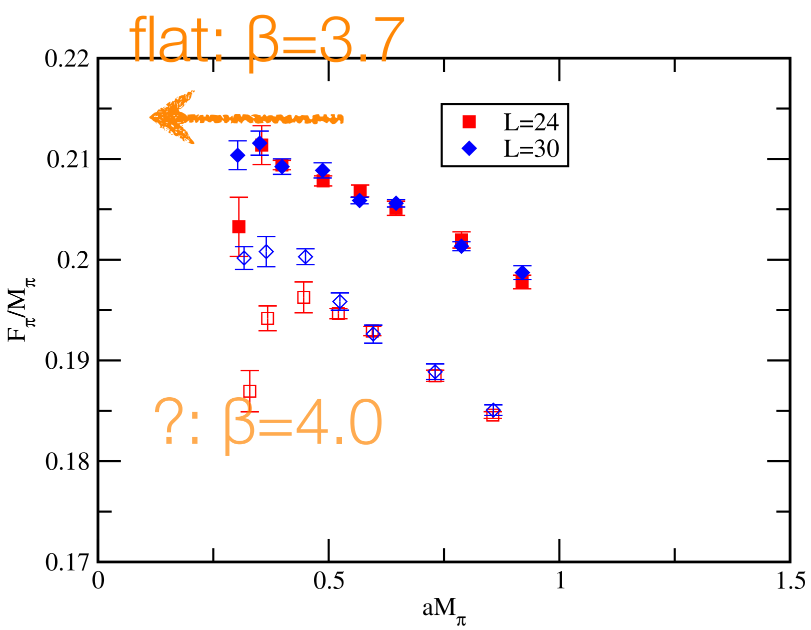
➡ a(β=3.7) / a(β=4.0) > 1

  - consistent with UV asymptotic freedom

- β=3.7 & 4.0: small mass (wider than F_π): consistent with hyper scaling (HS)
- mass dependence at the tail is due to non-universal mass correction to HS

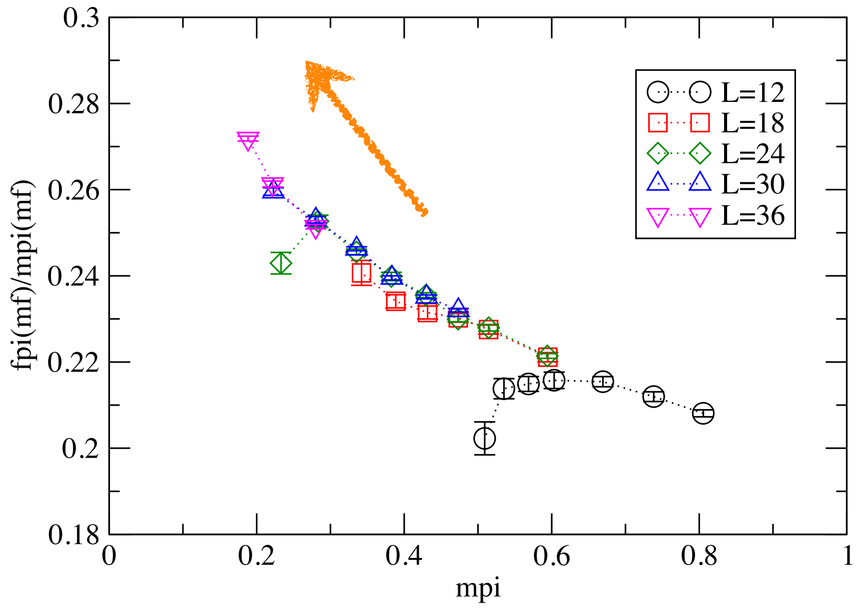
a crude analysis: F_π/M_π vs M_π leads to a likely scenario

N_f=12



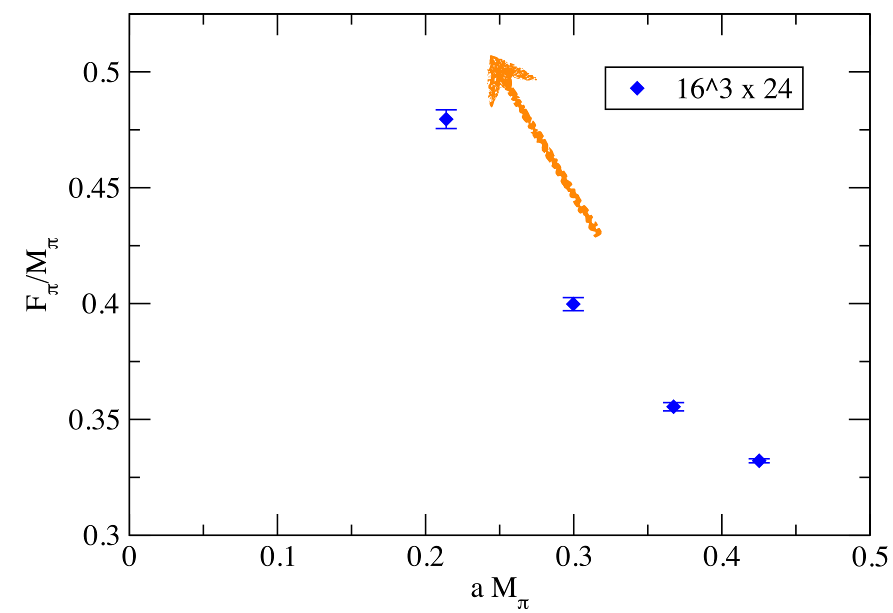
- conformality

N_f=8



- ~~chiral symmetry~~

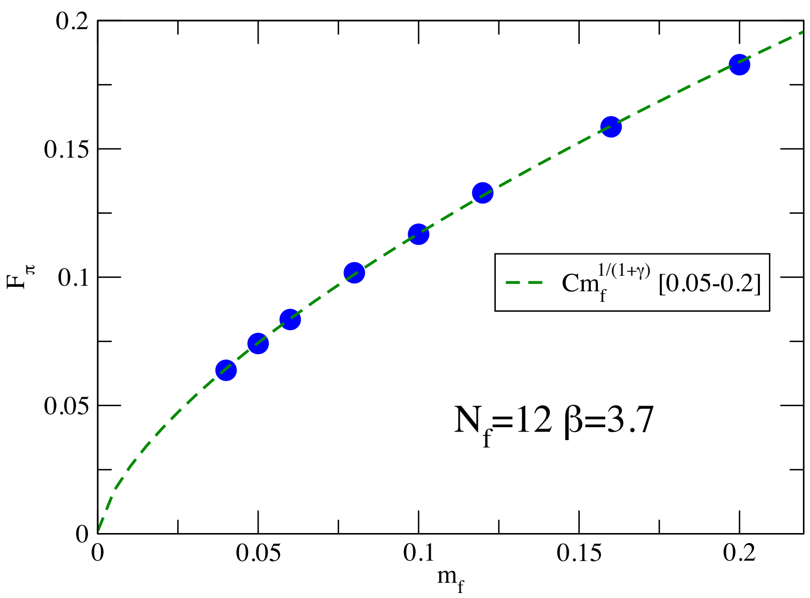
N_f=4



- ~~chiral symmetry~~

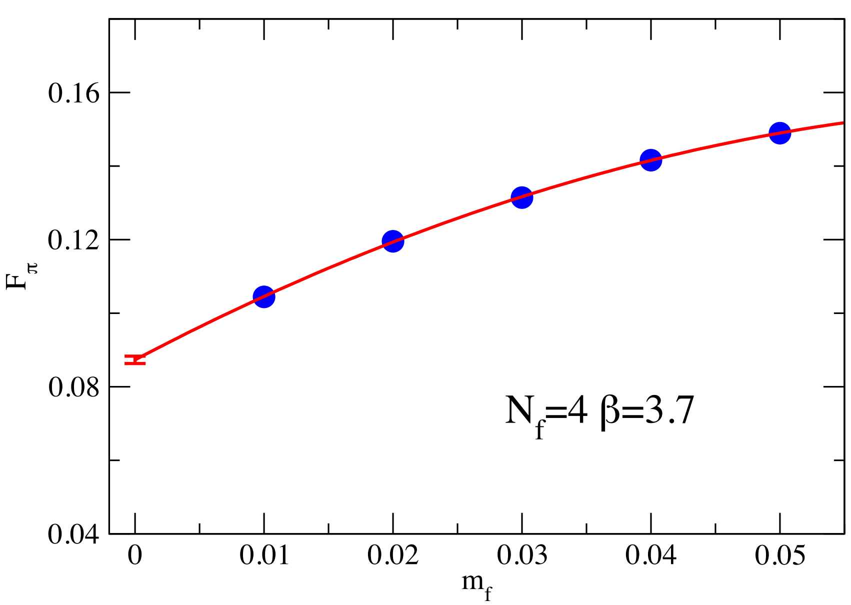
F_π vs m_f

N_f=12



- conformality
- $F_\pi \to Cm_f^{1/(1+\gamma)}$
- γ~0.5

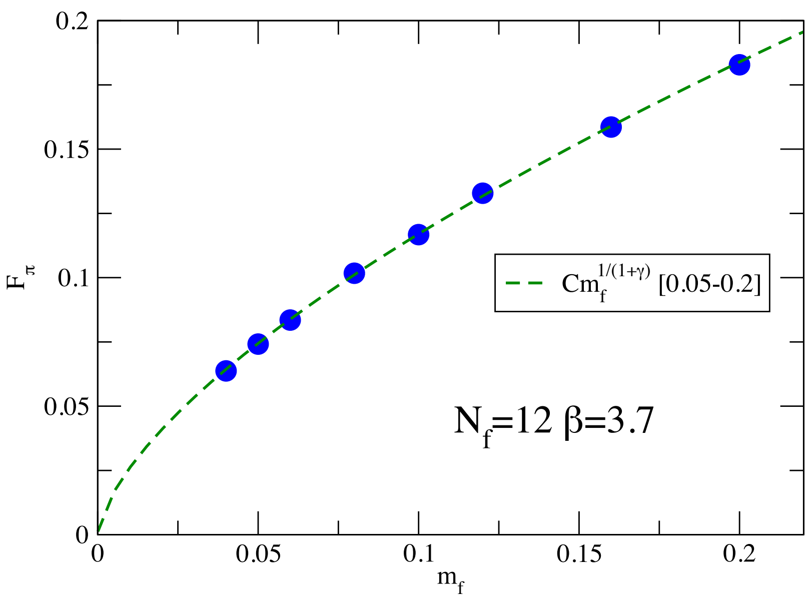
N_f=4



- ~~chiral symmetry~~
- $F_\pi \to F \neq 0$

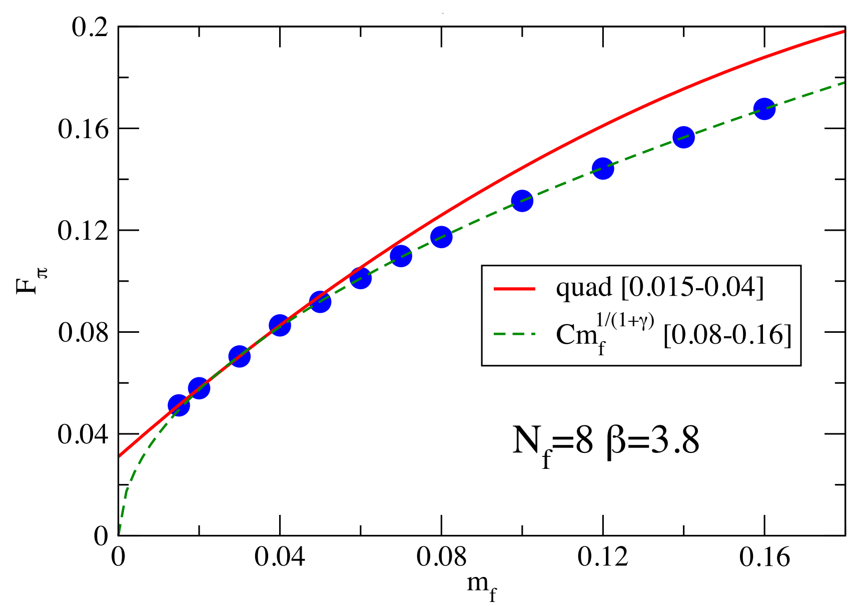
F_π vs m_f

N_f=12



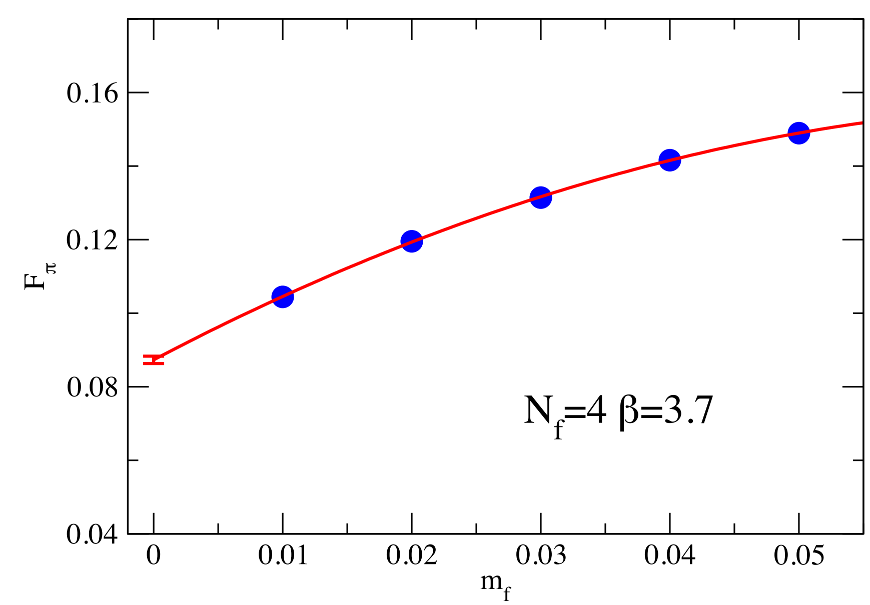
- ~~conformality~~
- $F_\pi \to C m_f^{1/(1+\gamma)}$
- γ~0.5

N_f=8



- ~~chiral symmetry~~
- $F_\pi \to F \neq 0$ $\quad m_f \to 0$
- $F_\pi \to C m_f^{1/(1+\gamma)}$ intermediate m_f
- γ~0.9

N_f=4



- ~~chiral symmetry~~
- $F_\pi \to F \neq 0$

conformal (finite size) scaling

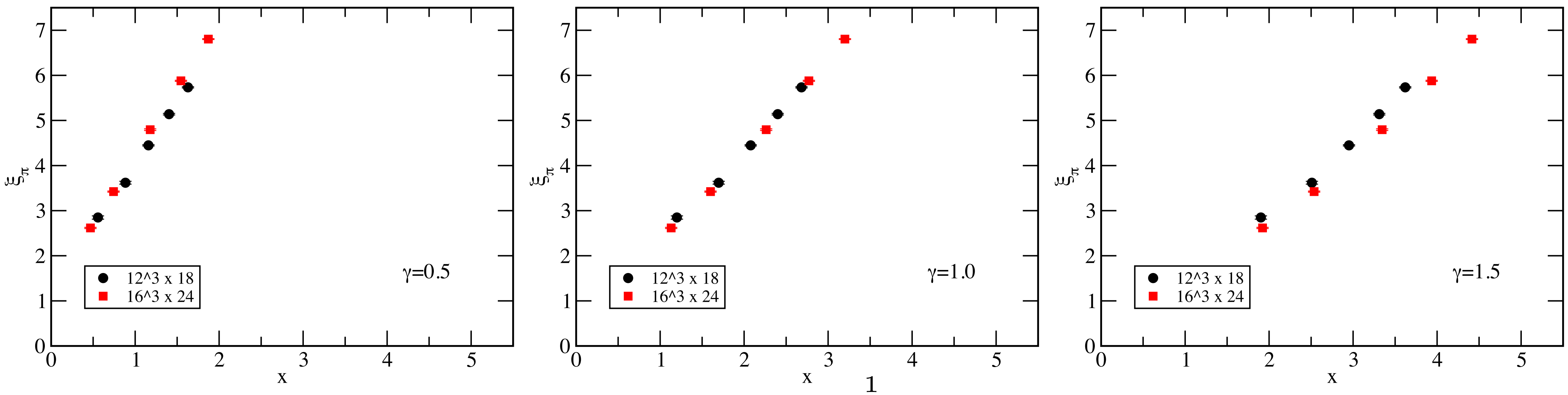
- Scaling dimension at IR fixed point [Wilson-Fisher]; Hyper Scaling [Miransky]
- mass dependence is described by anomalous dimensions at IRFP
  - quark mass anomalous dimension γ^*
  - operator anomalous dimension
- hadron mass and pion decay constant obey same scaling

$$M_H \propto m_f^{\frac{1}{1+\gamma^*}} \qquad\qquad F_\pi \propto m_f^{\frac{1}{1+\gamma^*}}$$

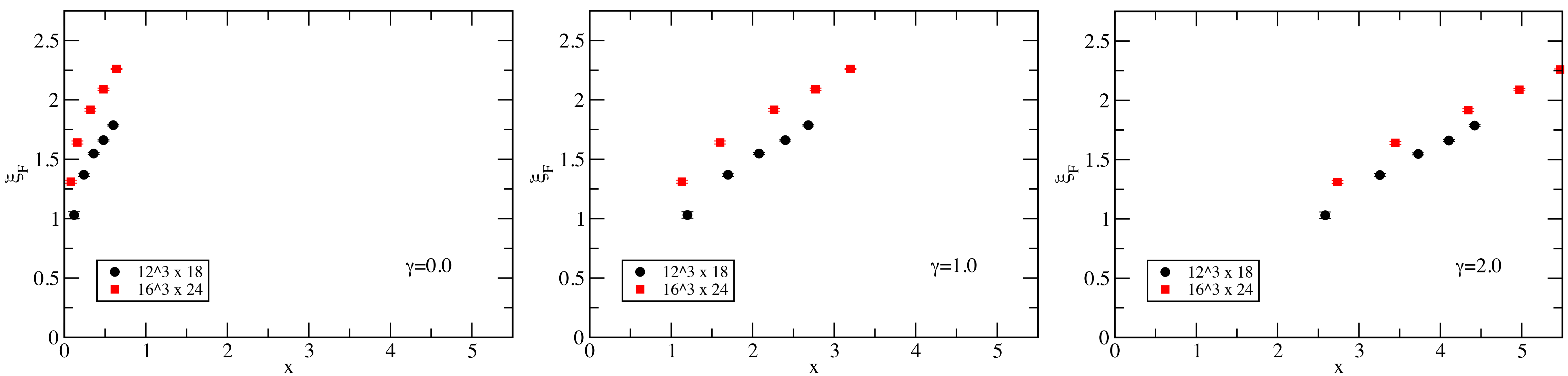
- finite size scaling in a L^4 box (DeGrand; Zwicky; Del Debbio et al)
  - scaling variable: $x = L m_f^{\frac{1}{1+\gamma^*}}$

$$L \cdot M_H = f_H(x) \qquad\qquad L \cdot F_\pi = f_F(x)$$

N_f=4 see if data align at some γ

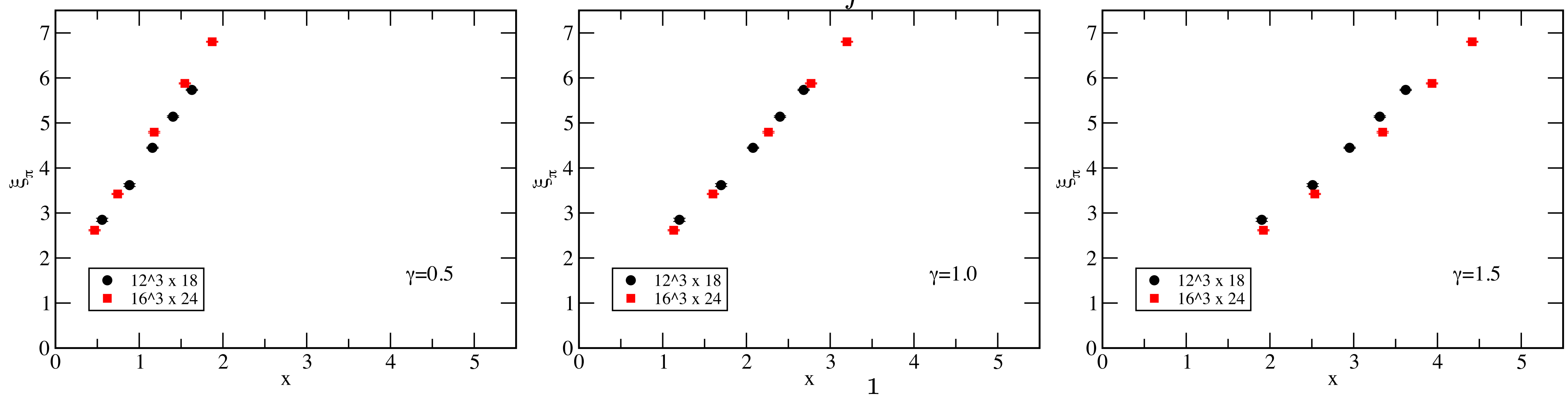


$$x = Lm_f^{\frac{1}{1+\gamma}}$$

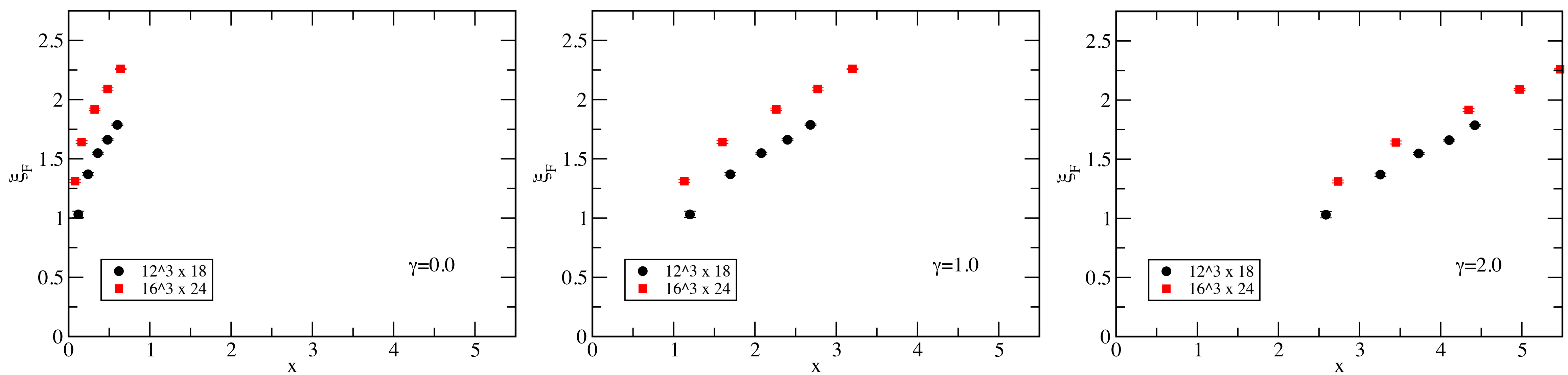


N_f=4 see if data align at some γ

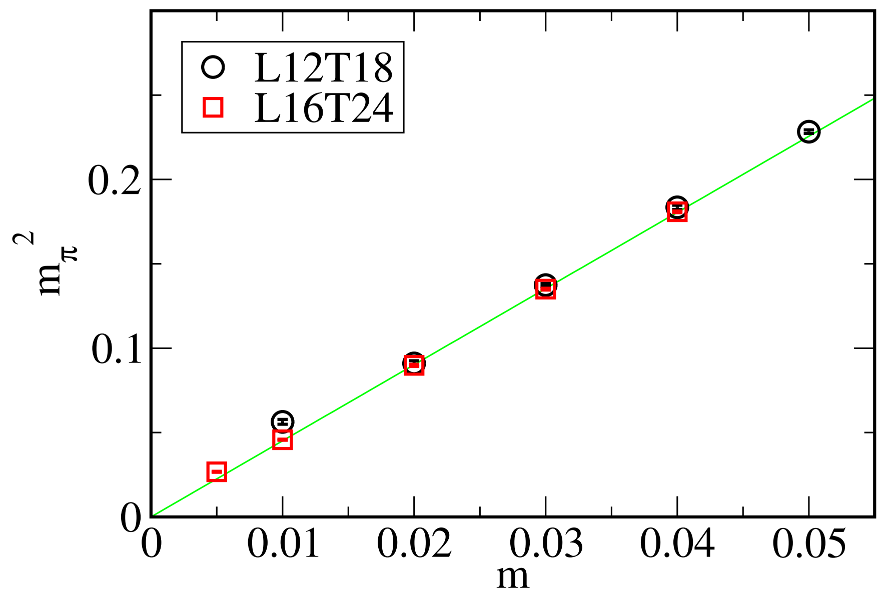
$$M_\pi L \propto m_f^{1/2} L$$

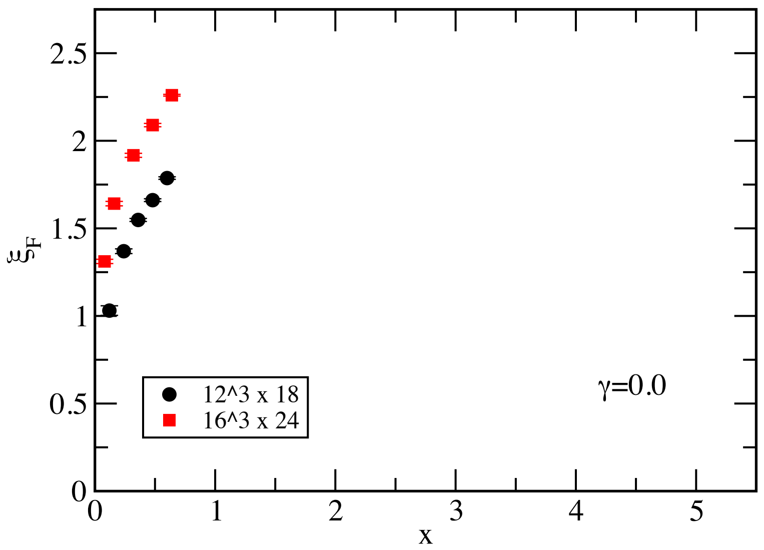


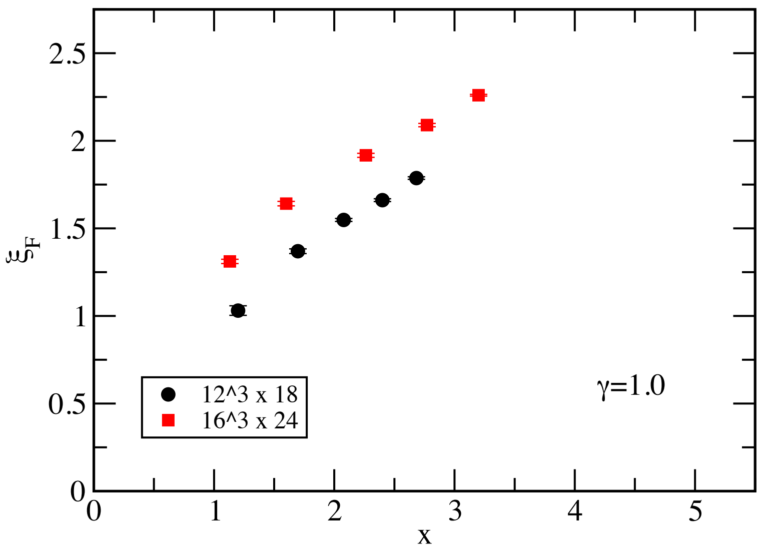
$$x = L m_f^{\frac{1}{1+\gamma}}$$

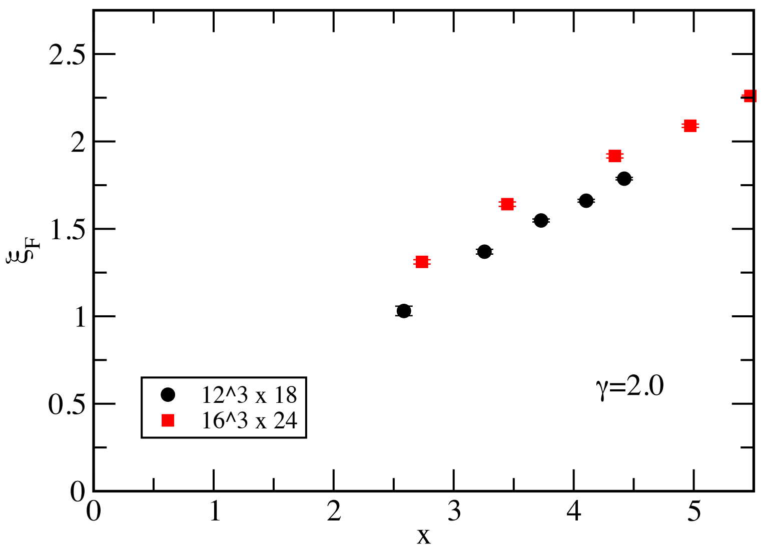


N_f=4 see if data align at some γ

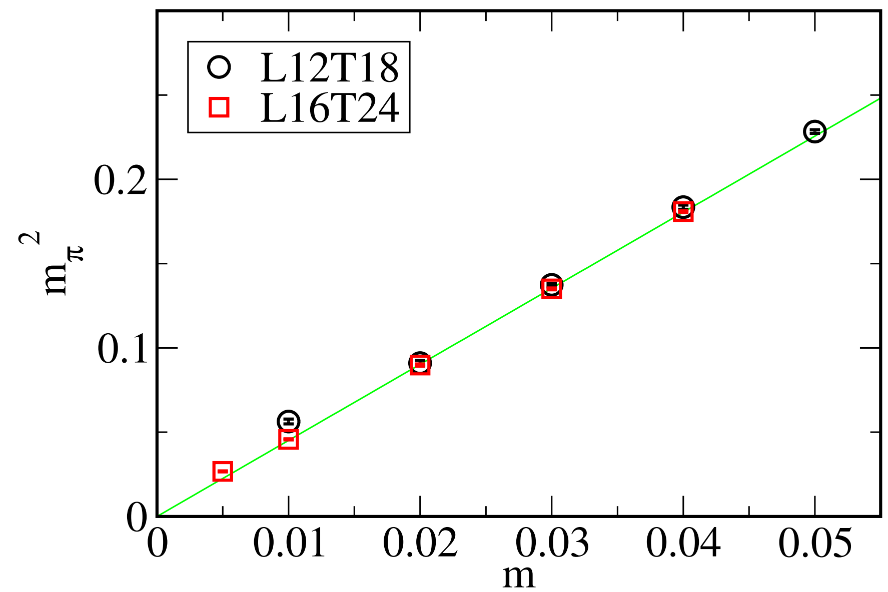


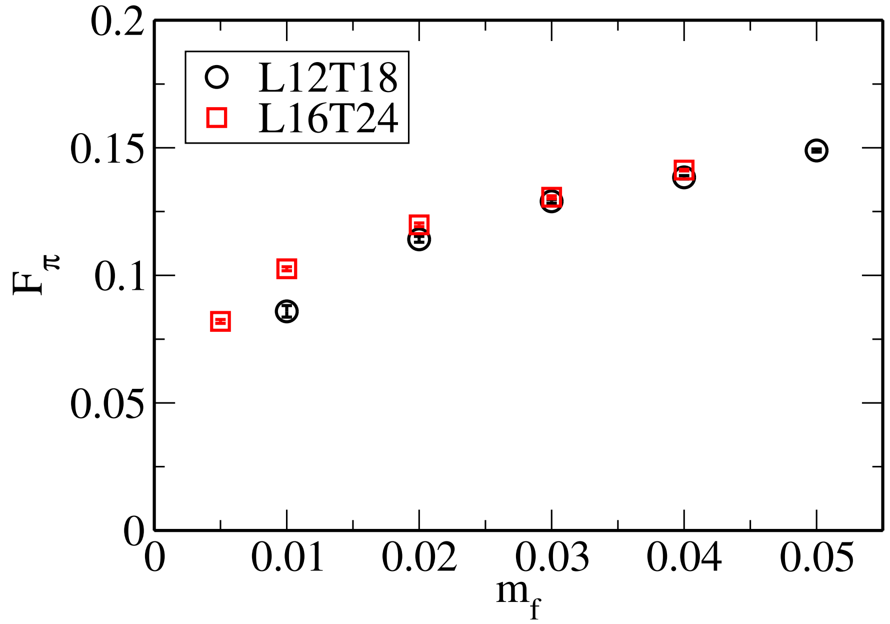






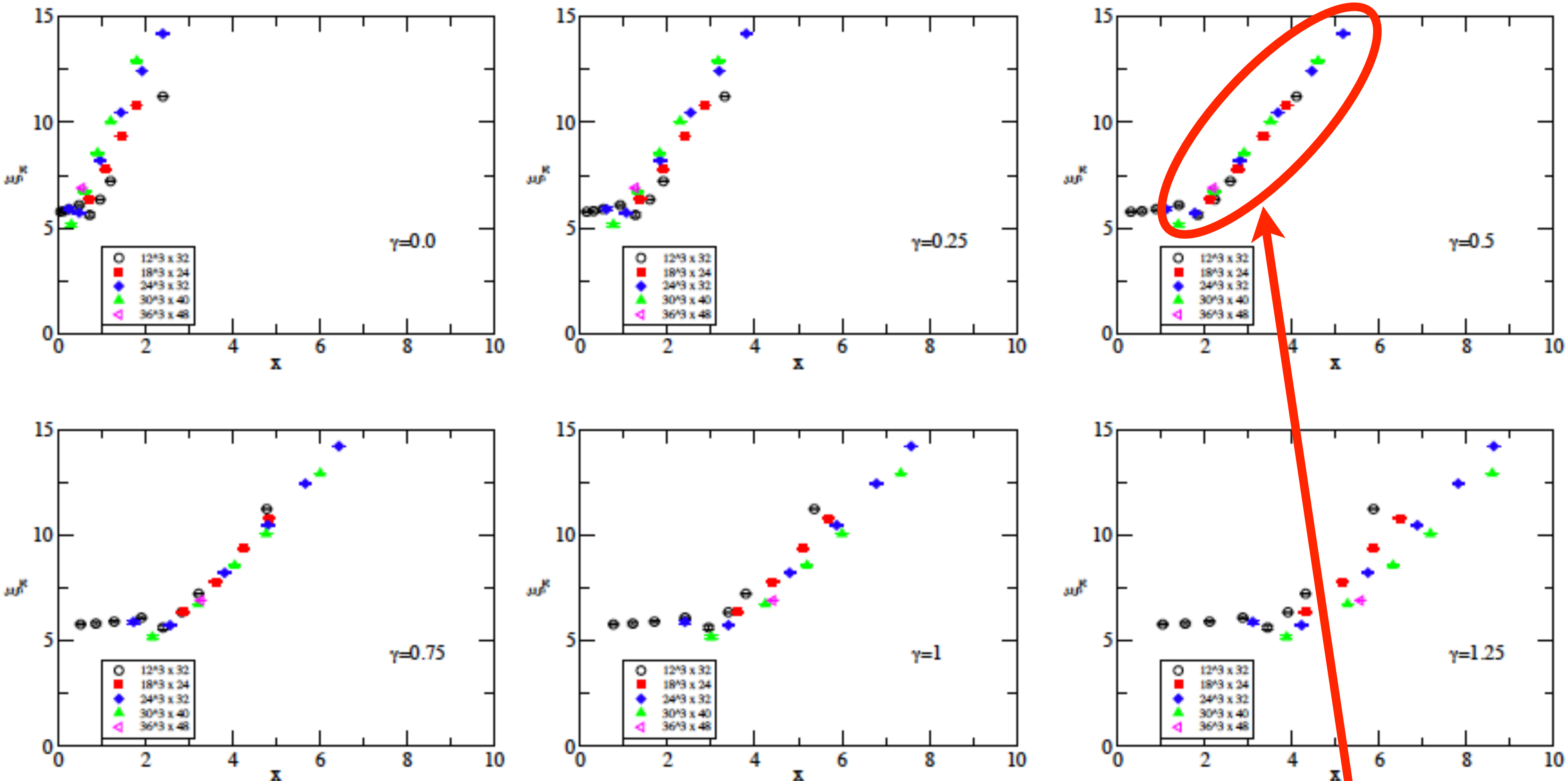
N_f=4 see if data align at some γ





N_f=8 see if data align at some γ: M_π

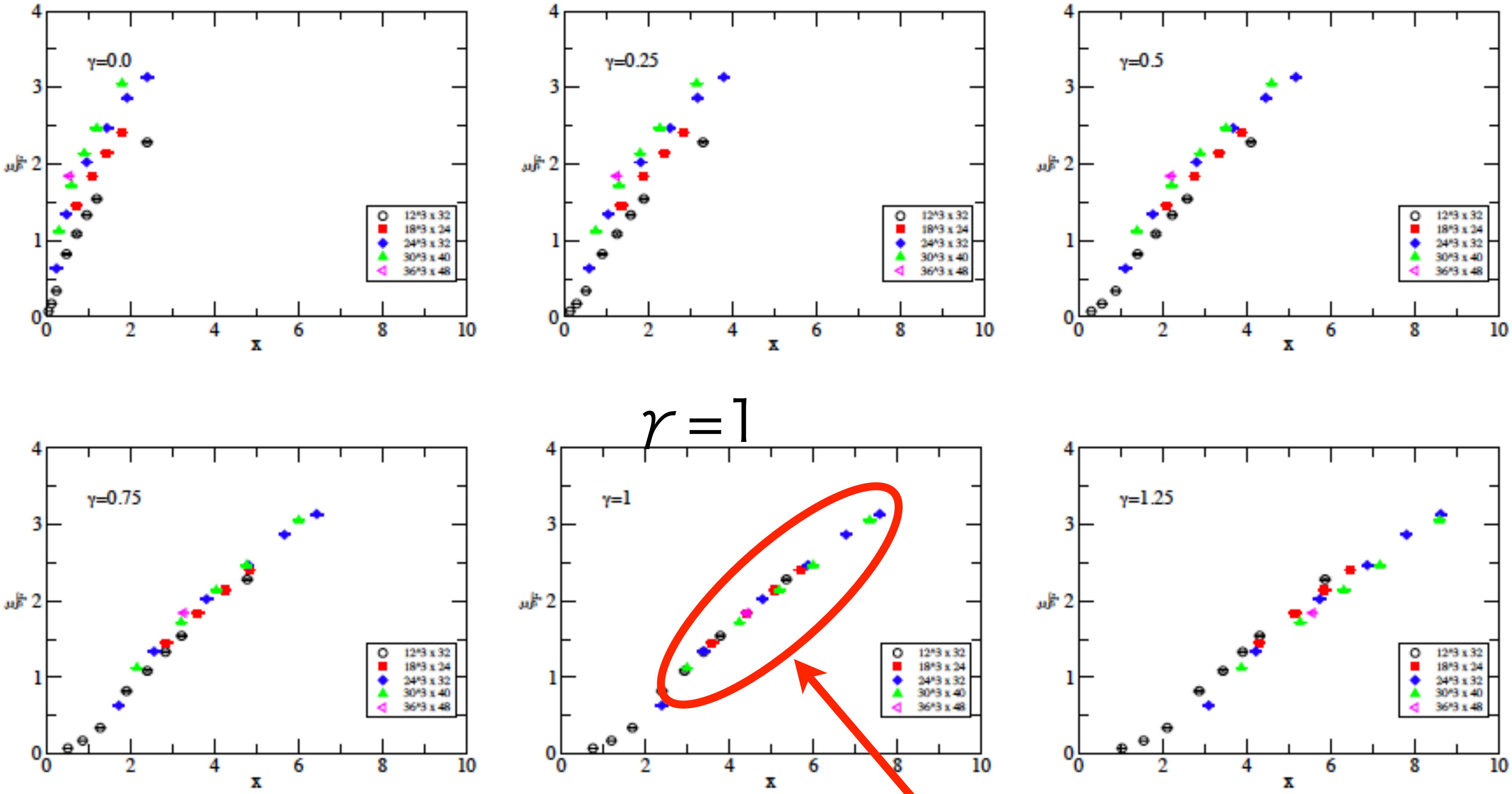
γ =0.5



good alignment

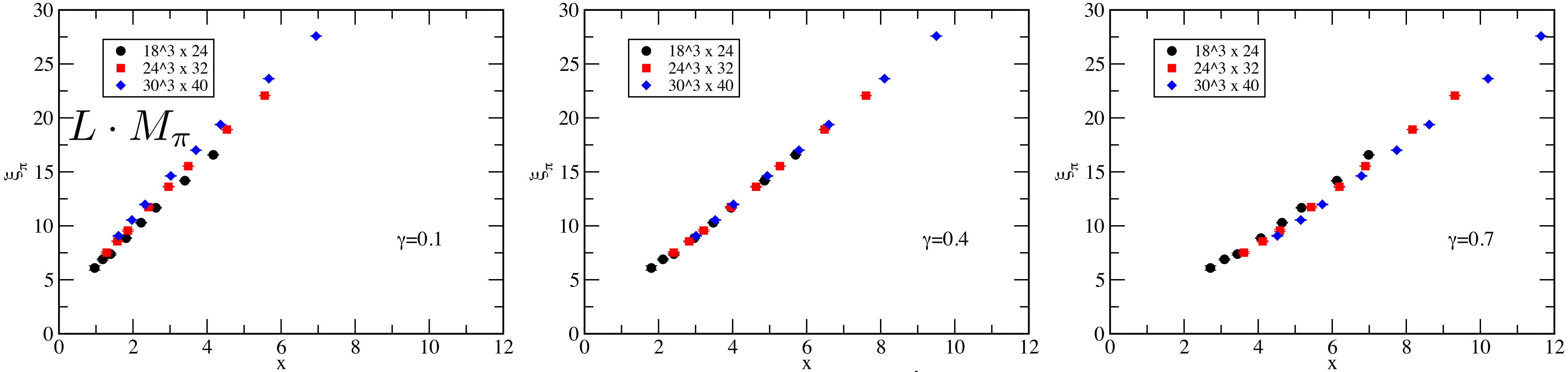
N_f=8 see if data align at some γ: F_π

$\gamma=1$

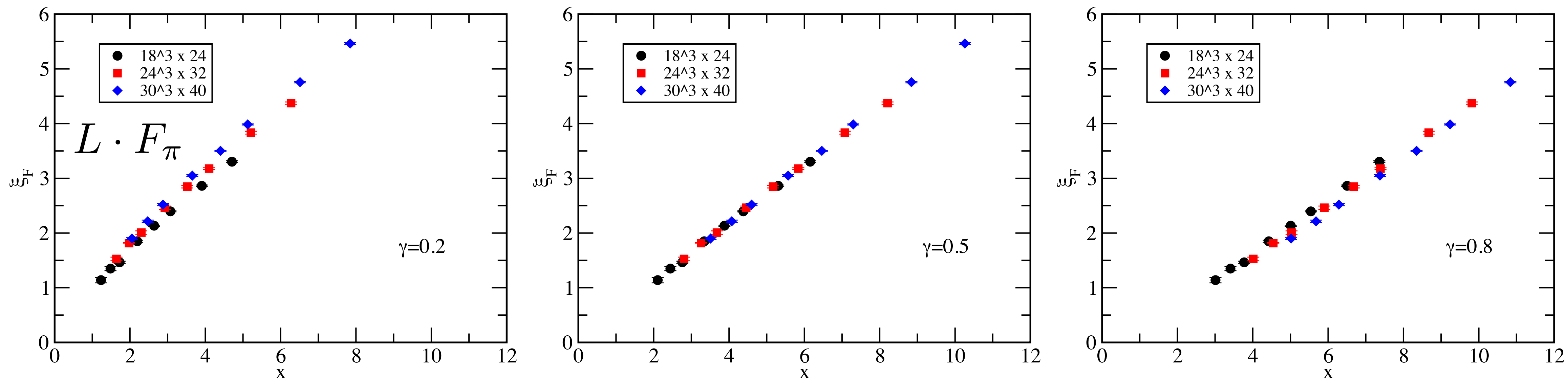


good alignment

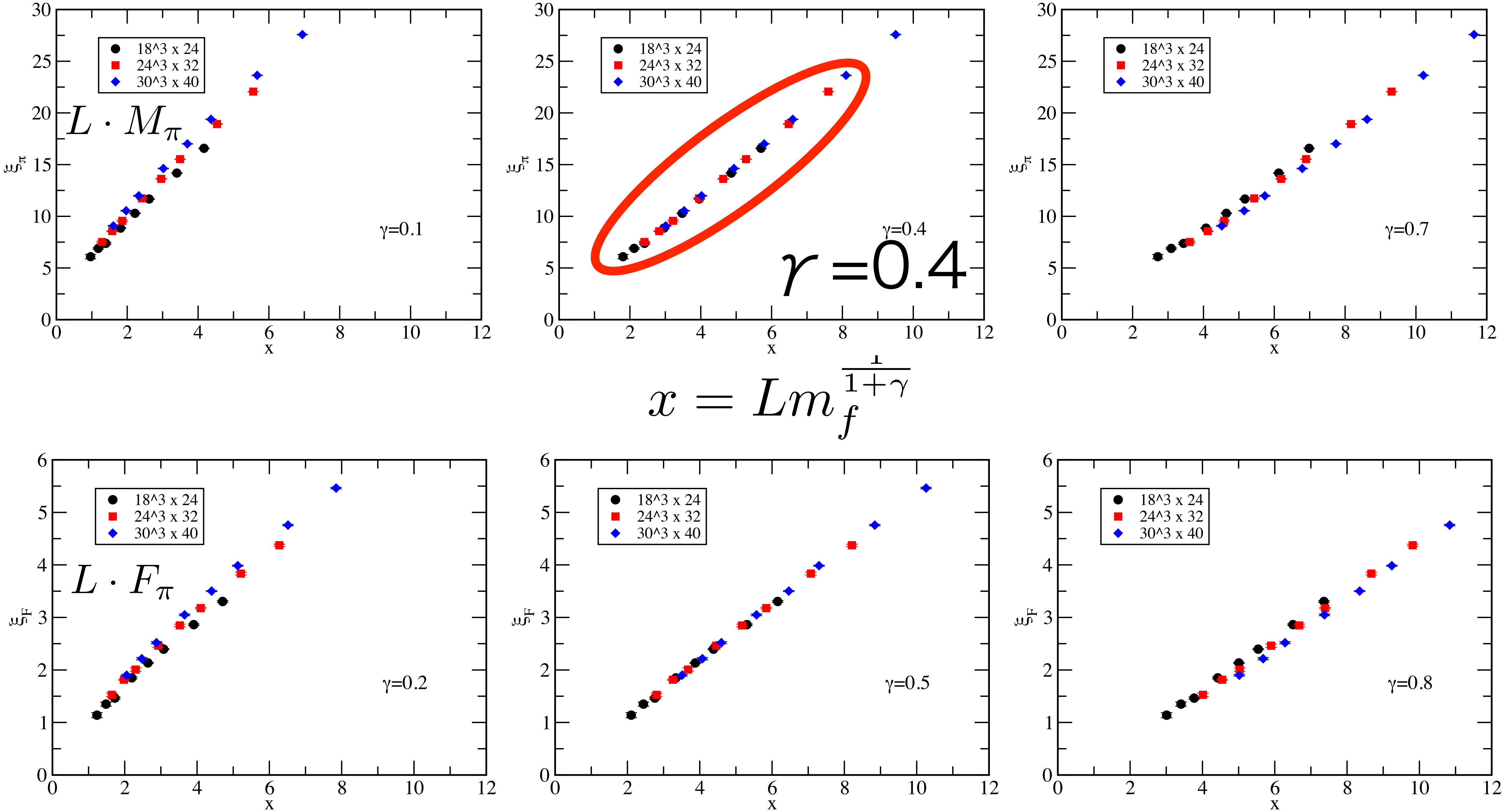
N_f=12 see if data align at some γ



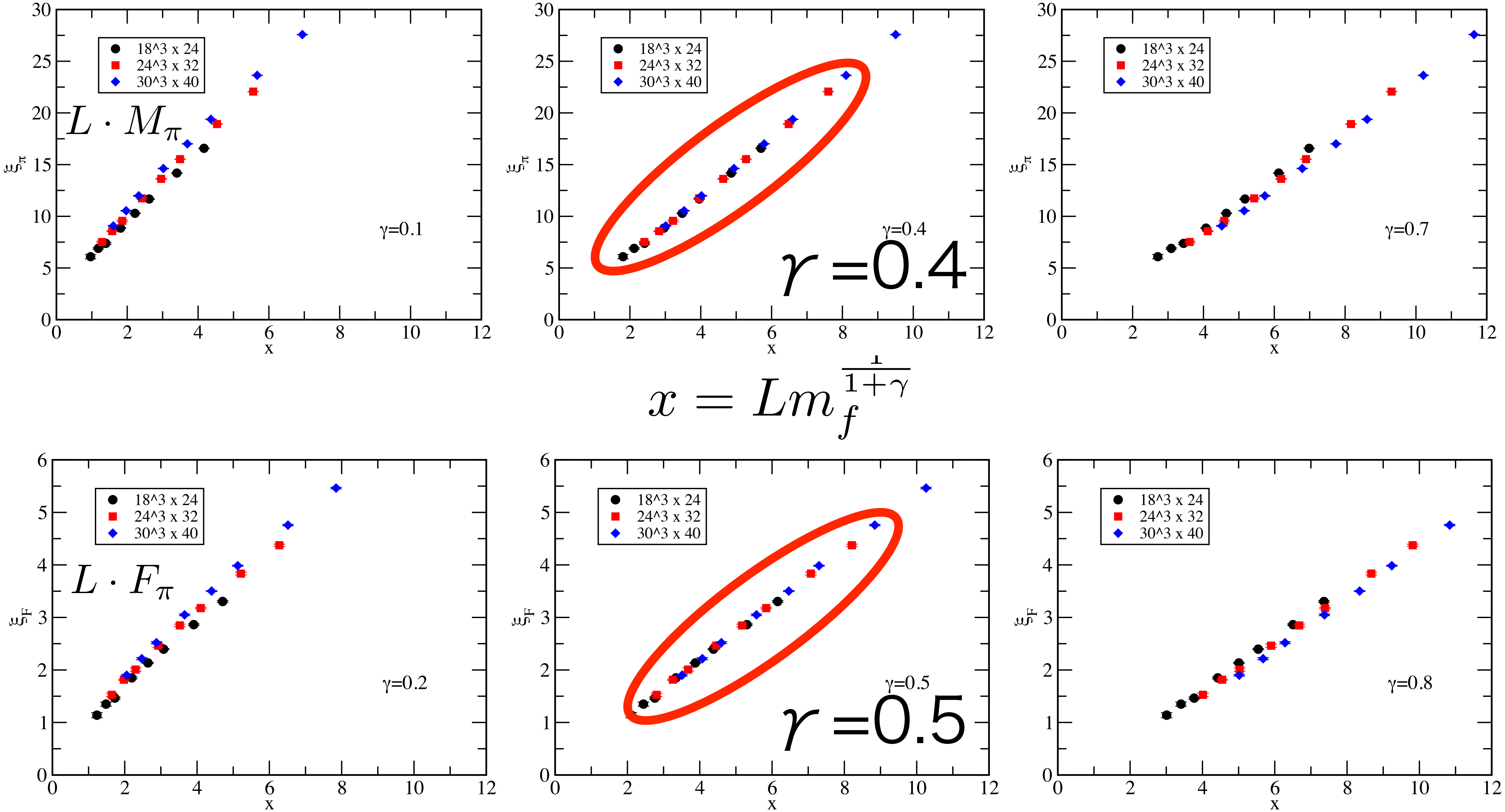
$$x = Lm_f^{\frac{1}{1+\gamma}}$$



N_f=12 see if data align at some γ



N_f=12 see if data align at some γ



measure of the “alignment” without resorting to a model

measure of the “alignment” without resorting to a model

- γ of optimal alignment will minimize:

$$P_p(\gamma) = \frac{1}{\mathcal{N}} \sum_K \sum_{j \notin K} \frac{|\xi_p^j - f_p^{(K)}(x_j)|^2}{\delta^2 \xi_p^j}$$

  - $\xi_p = LM_p$ for $p = \pi, \rho$; $\xi_F = LF_\pi$
  - $f_p(x)$: interpolation .... linear
    - (quadratic for a systematic error)
- if ξ^j is away from $f(x_i)$ by $\delta\, \xi^j$ as average → P=1
- optimal γ from the minimum of P
- similar definition of the measure: DeGrand, Giedt & Weinberg

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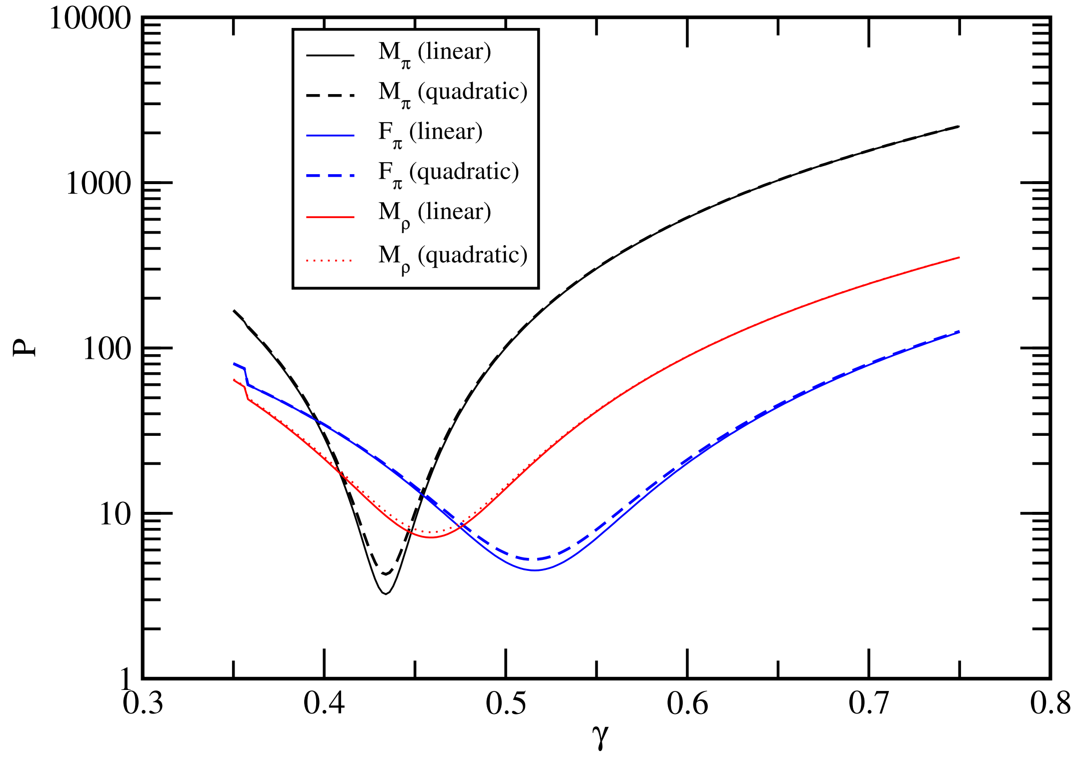
P(γ) for M_π,F_π,M_ρ at β=3.7



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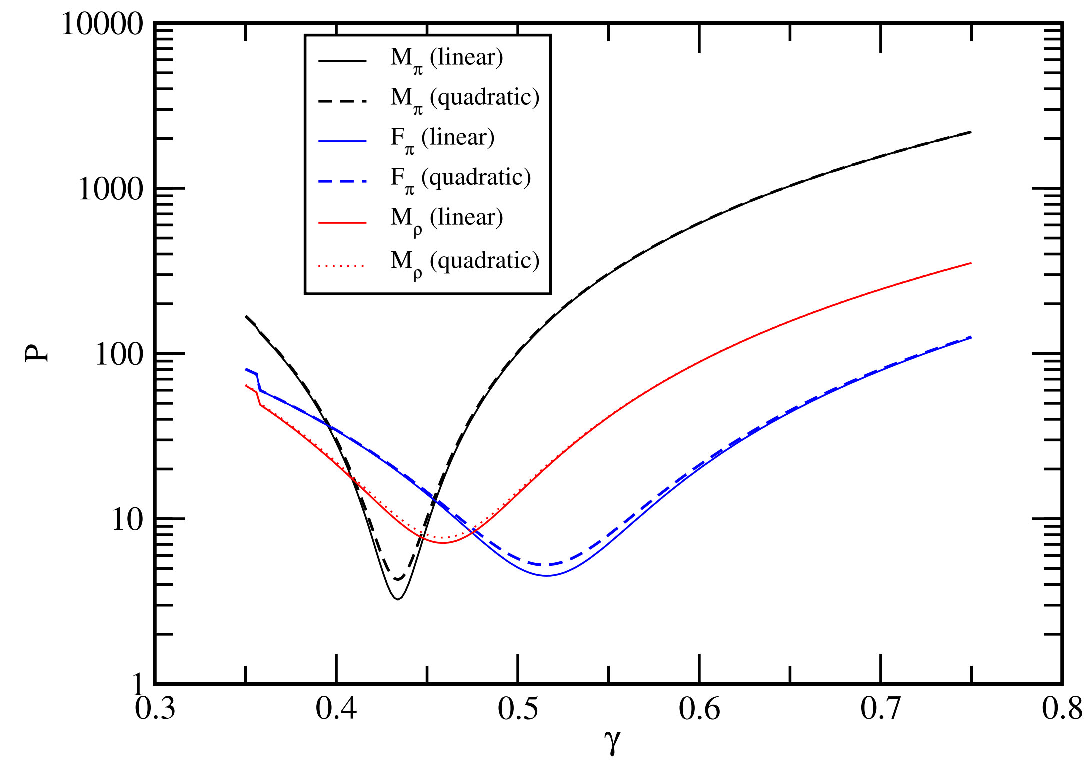
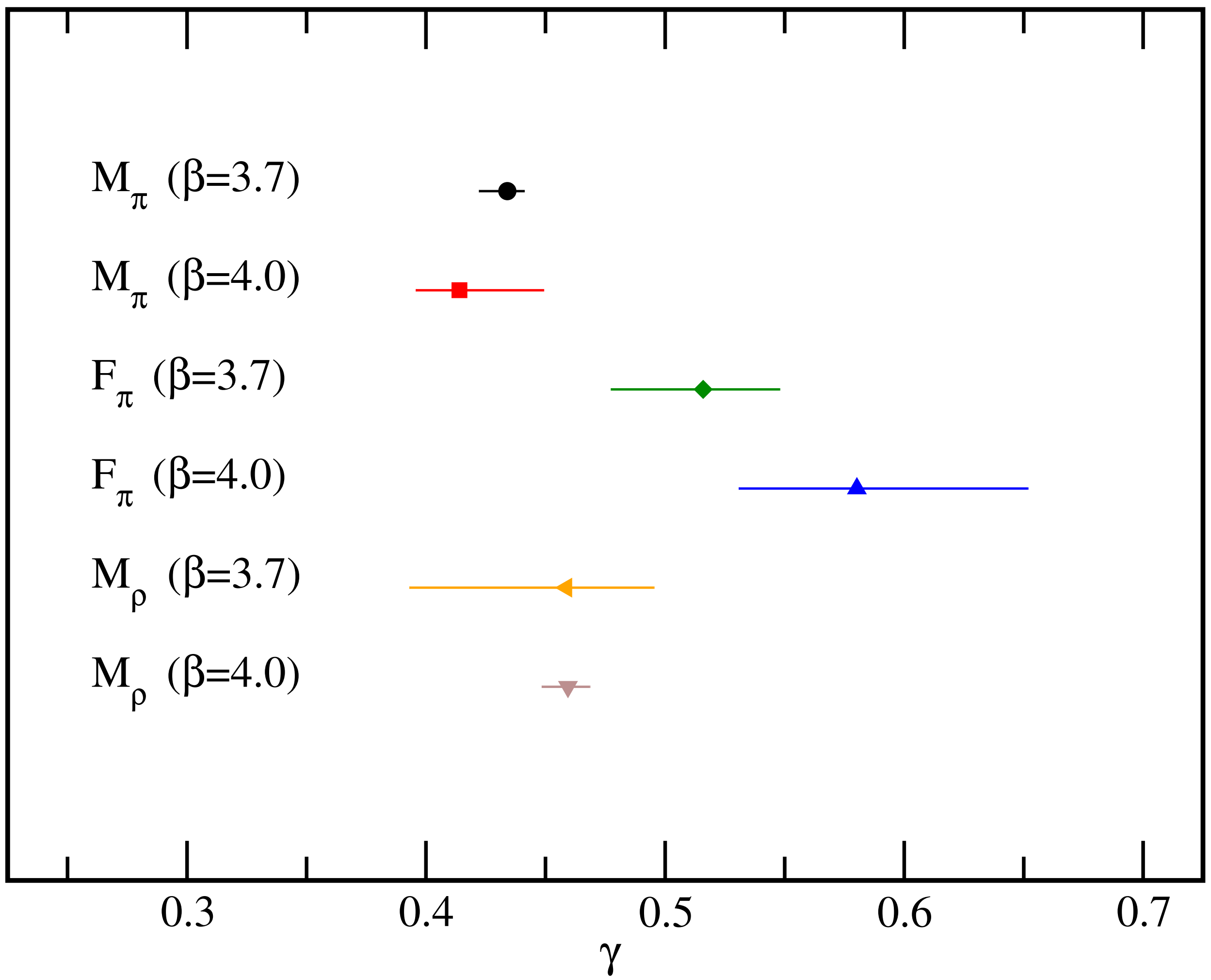
- similar definition of the measure: DeGrand, Giedt & Weinberg
- systematic error due to small L, large m estimated by examining the x and L range dependence

P(γ) for Mπ,Fπ,Mρ at β=3.7

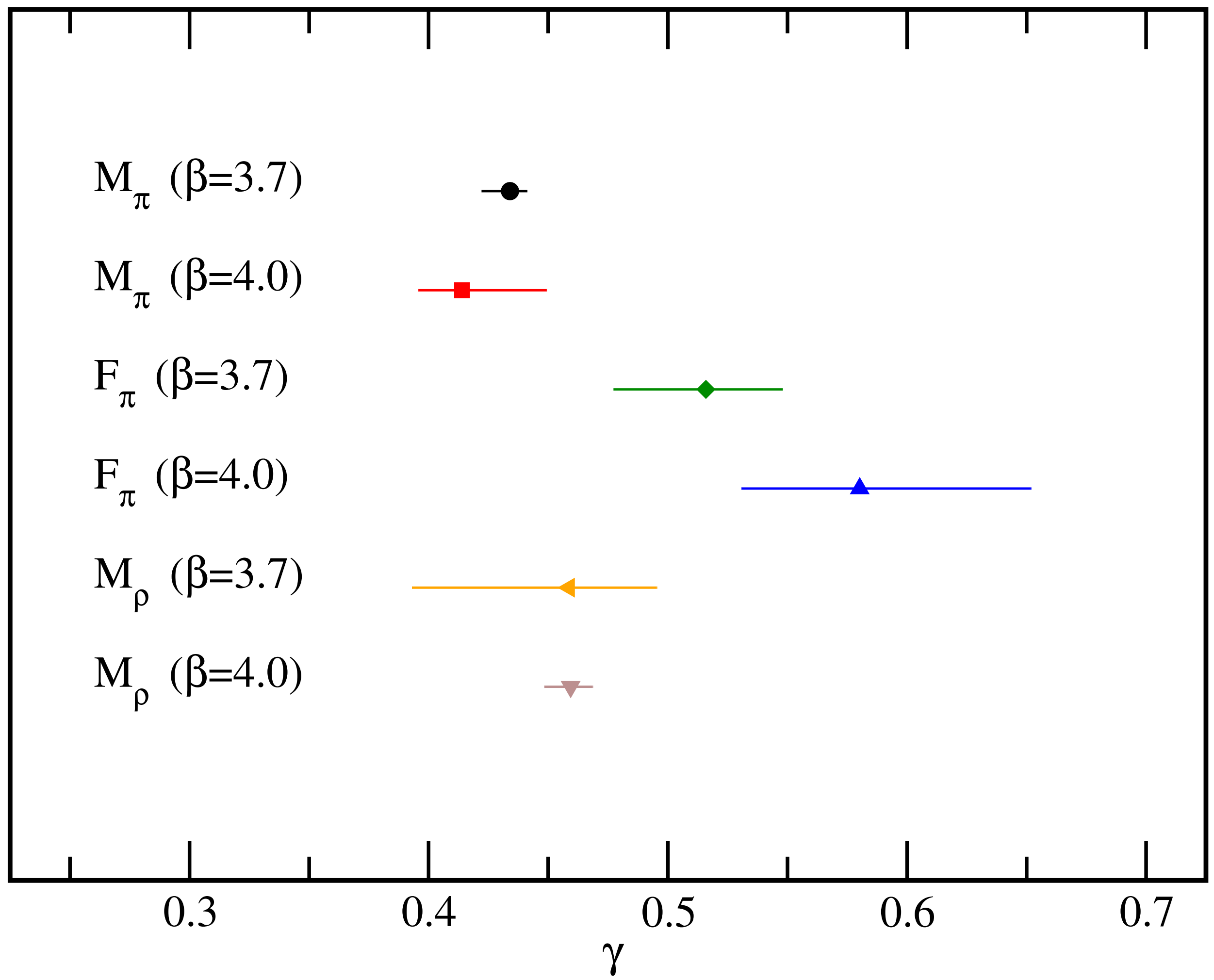


summary of γ from P(γ) for N_f=12



PRD 86 (2012)

summary of γ from P(γ) for N_f=12



PRD 86 (2012)

- γ: consistent with 2 σ level except for F_π at β=4.0

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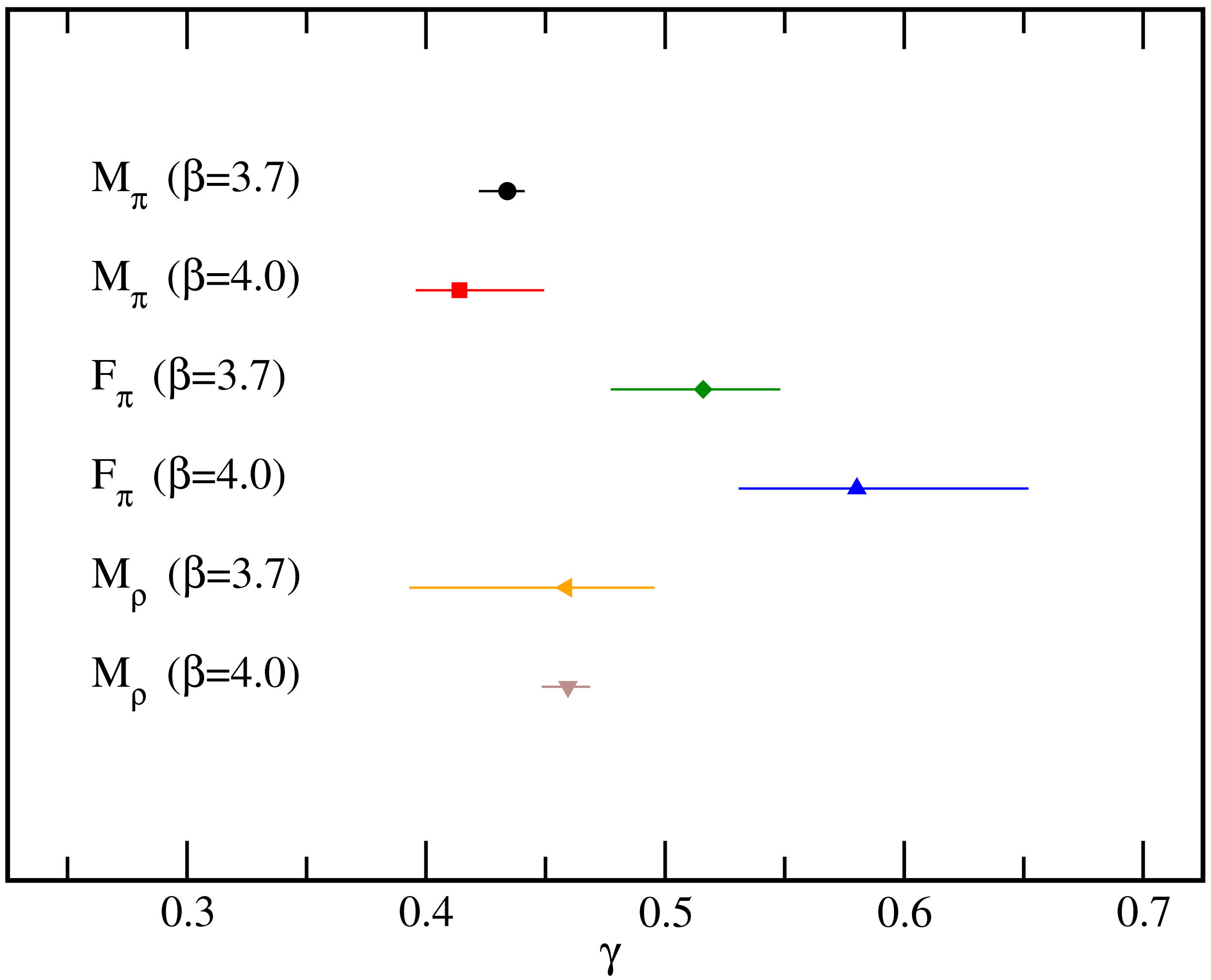

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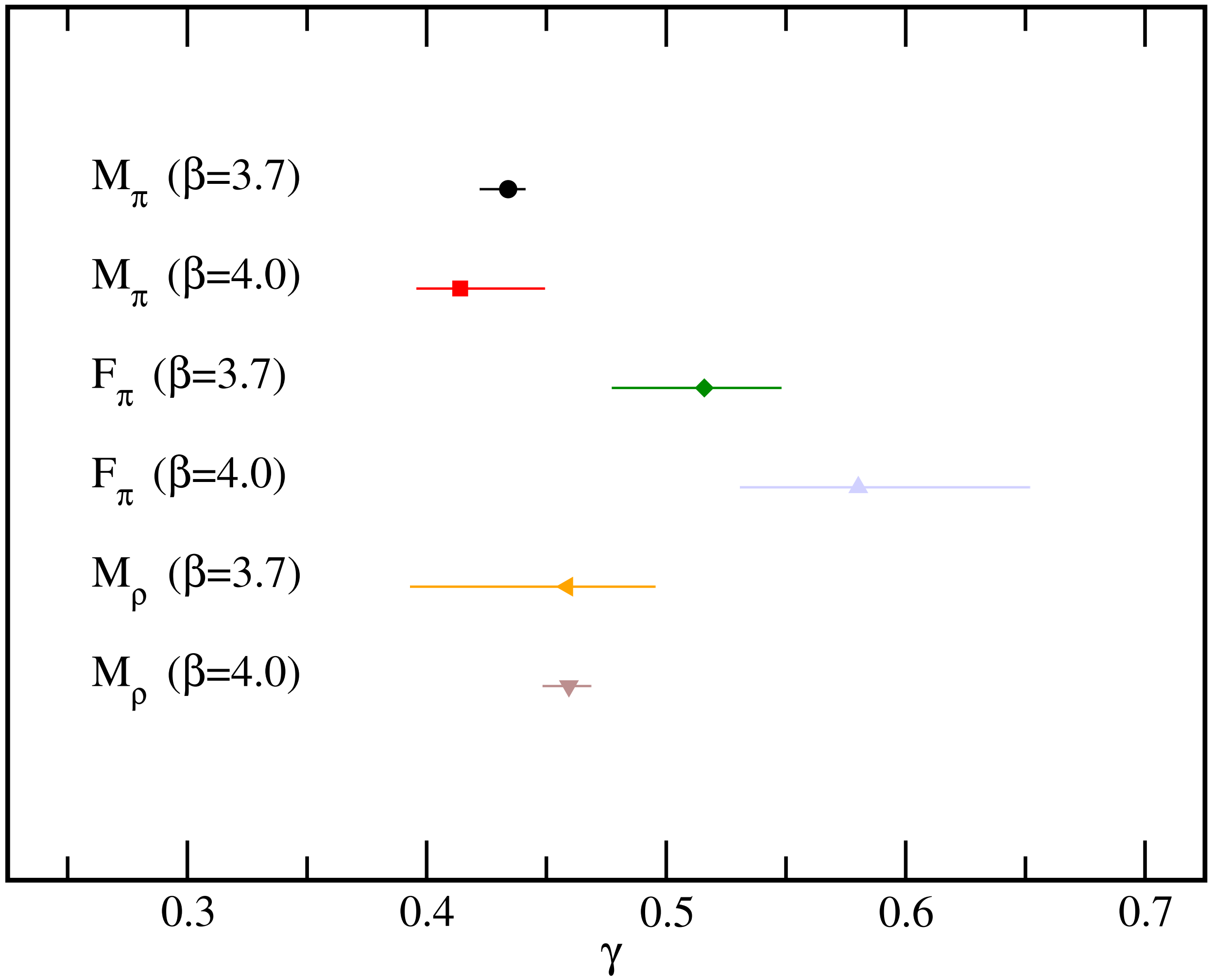

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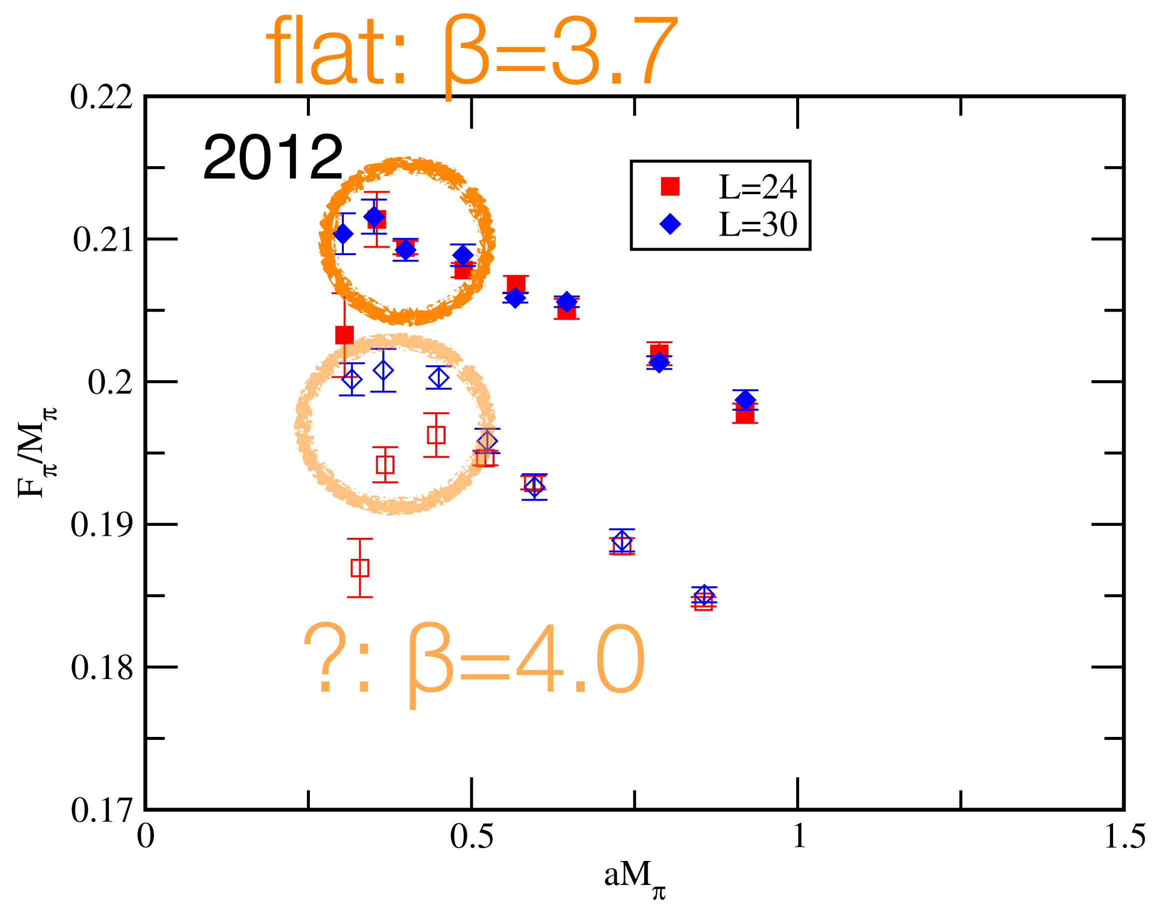

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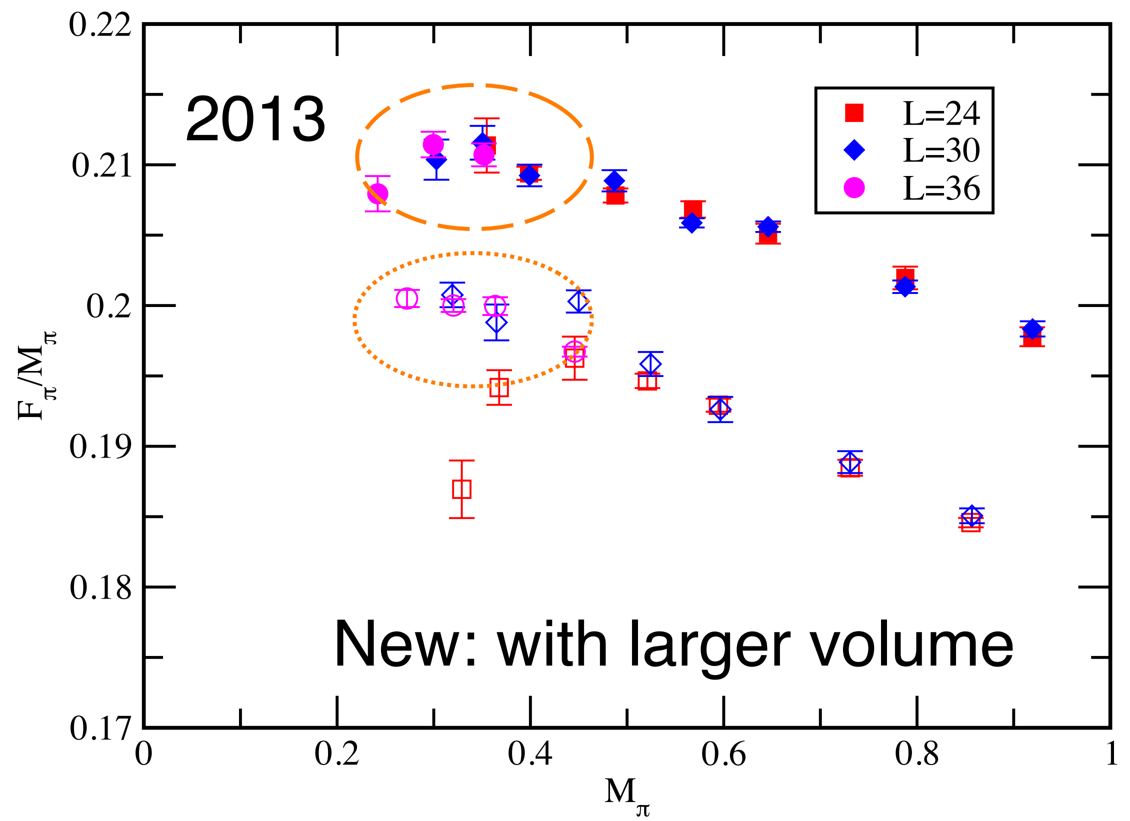

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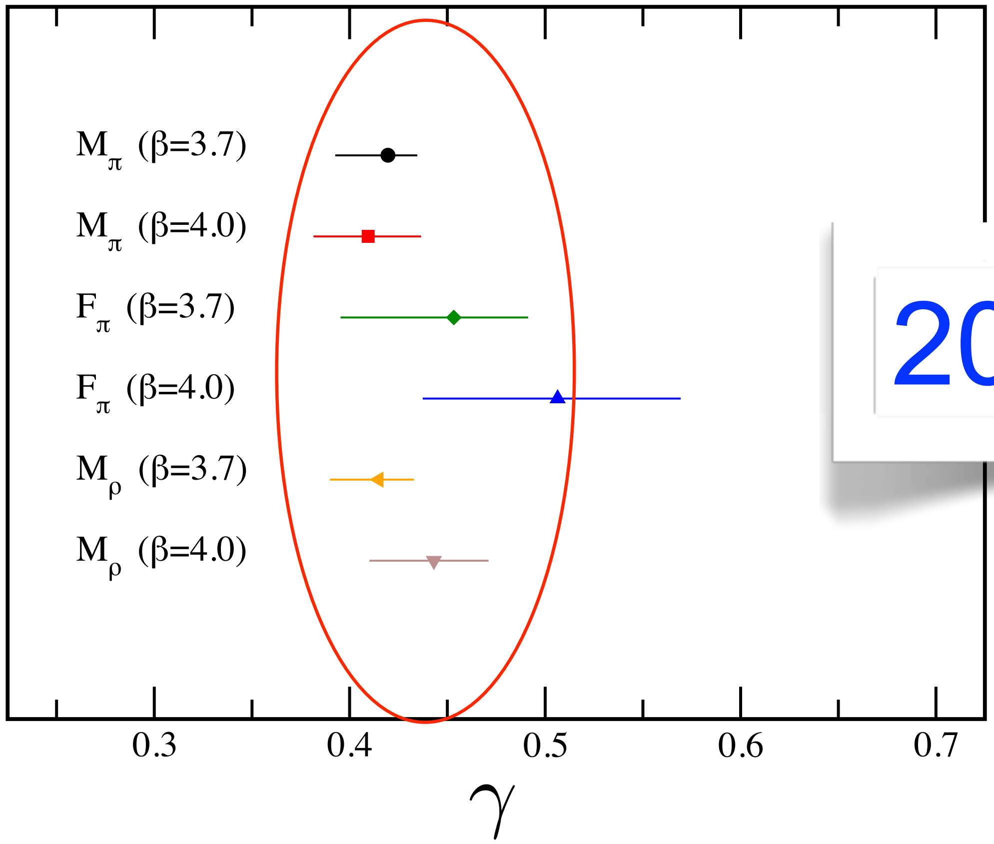

2013 Update

- γ: consistent with 2 σ level except for F_π at β=4.0
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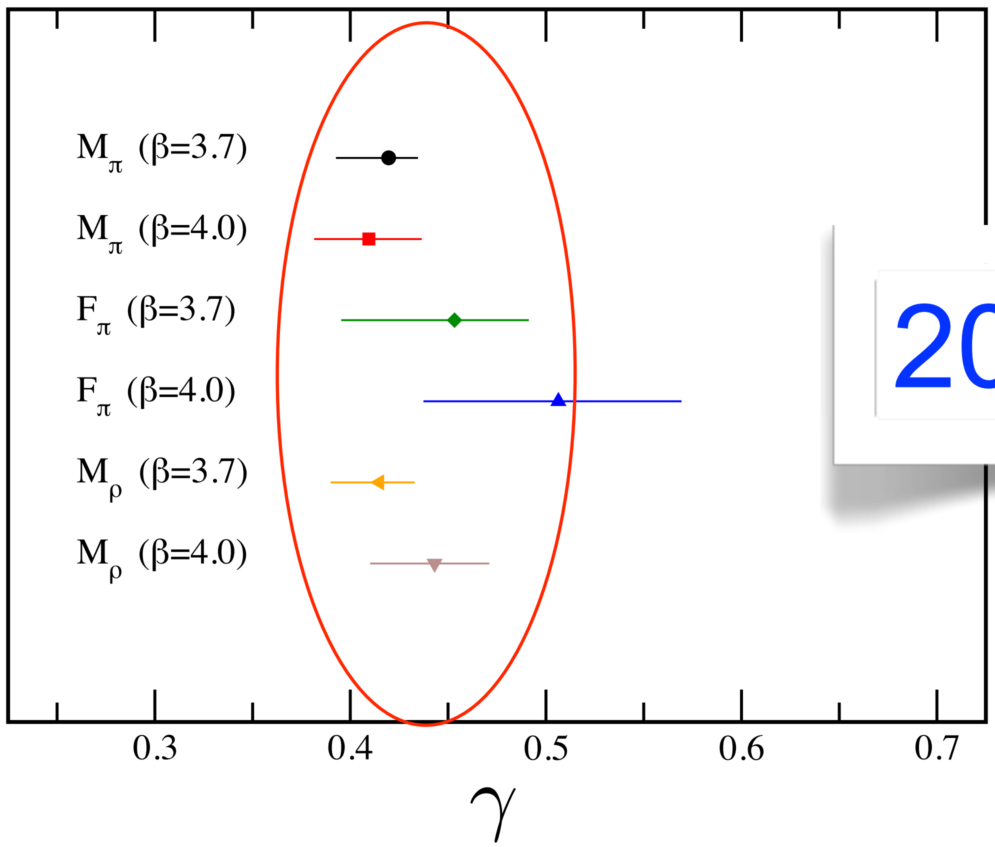

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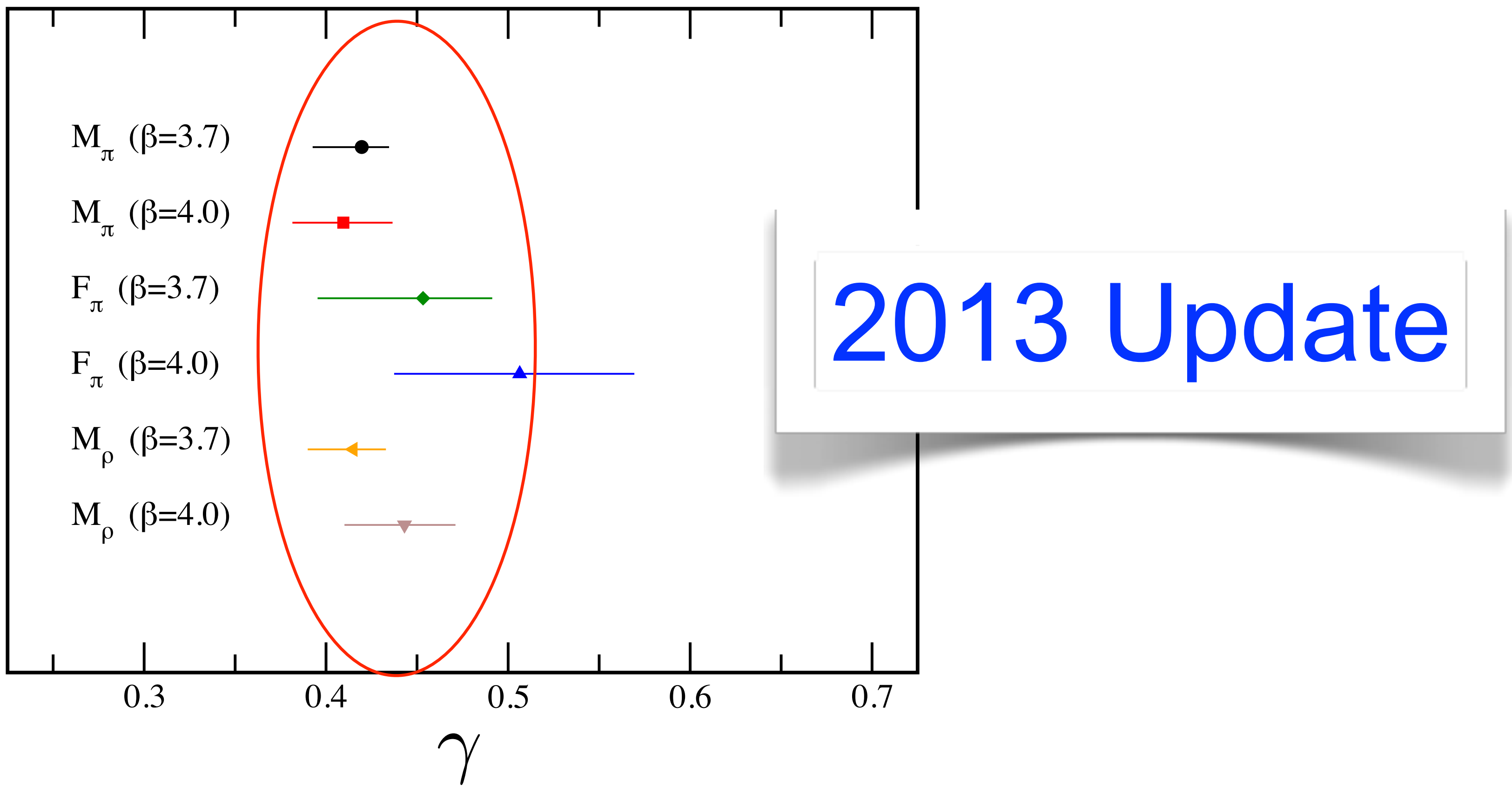

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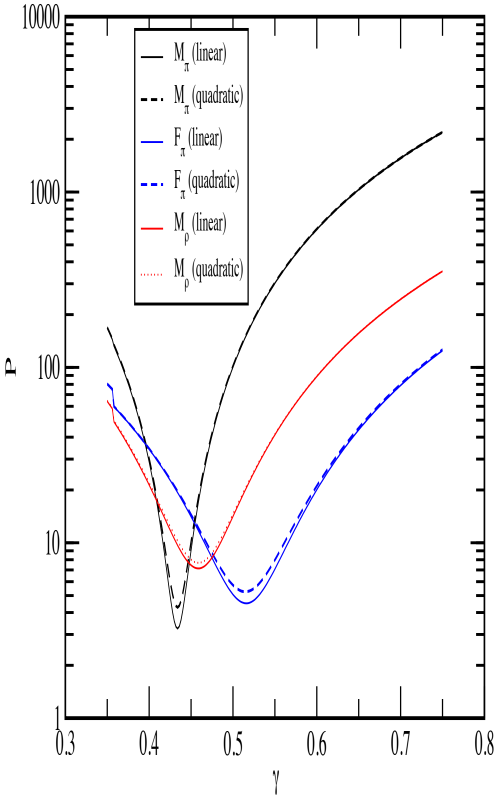
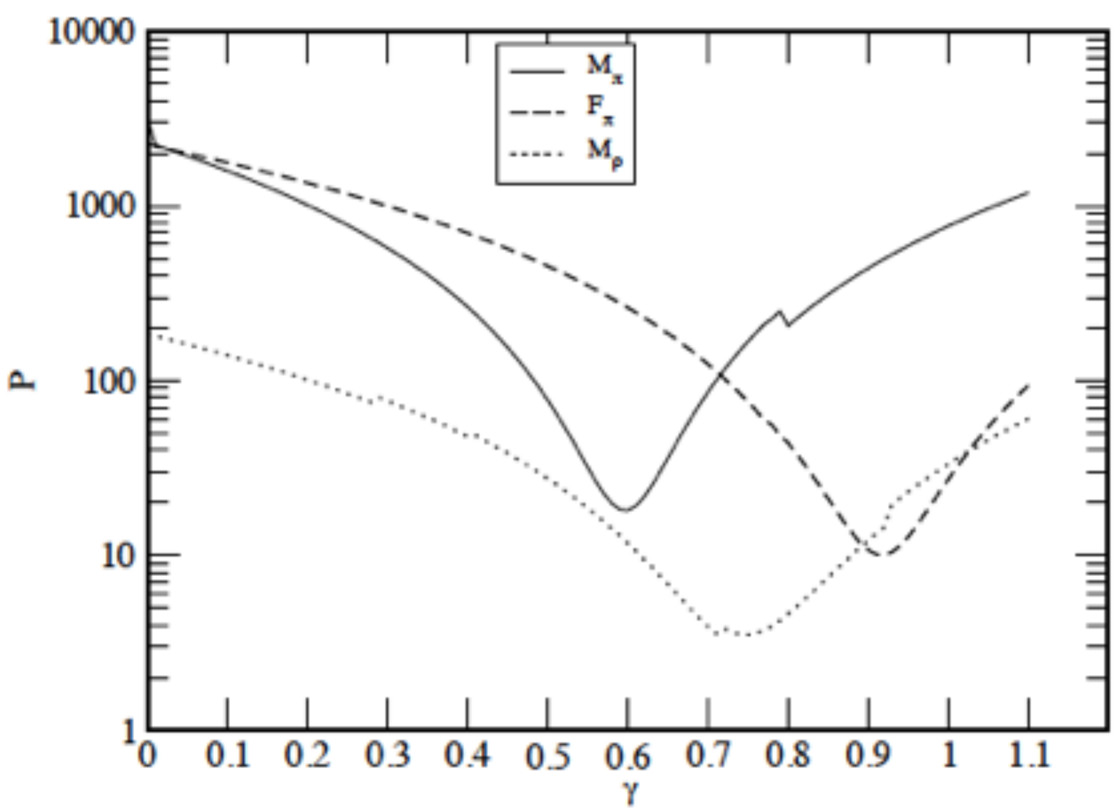
$P(\gamma)$ analysis for Nf=8



Nf=12

quantity	γ
M_π	0.434(4)
F_π	0.516(12)
M_ρ	0.459(8)

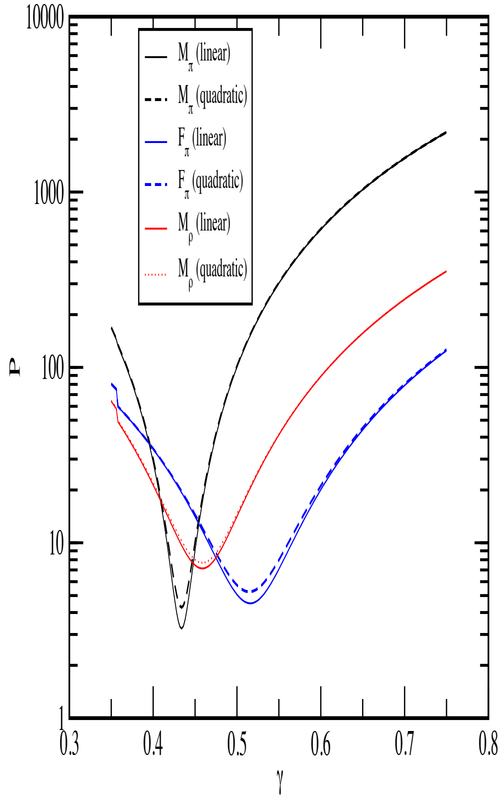
statistical error only



Nf=8

quantity	γ
M_π	0.593(2)
F_π	0.955(4)
M_ρ	0.820(20)

$P(\gamma)$ analysis for N_f=8



N_f=12

quantity	r
M_π	0.434(4)
F_π	0.516(12)
M_ρ	0.459(8)

statistical error only

N_f=8

quantity	r
M_π	0.593(2)
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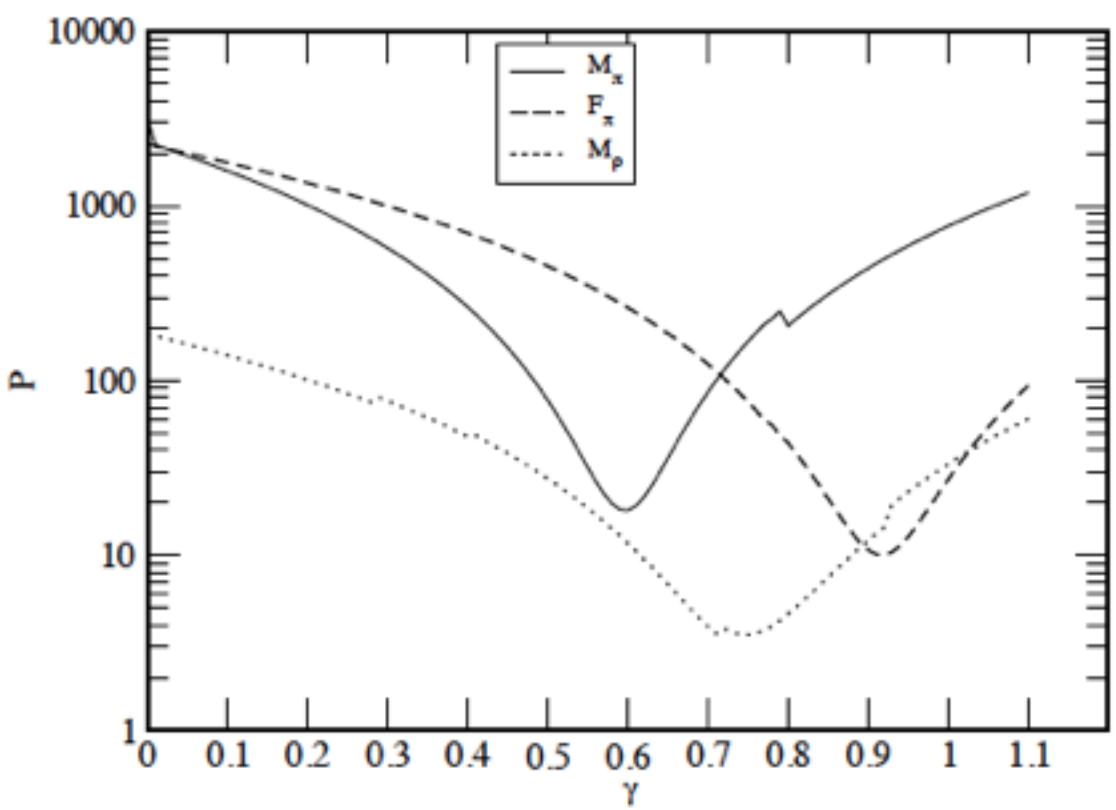
- Optimal γ obtained for each quantity



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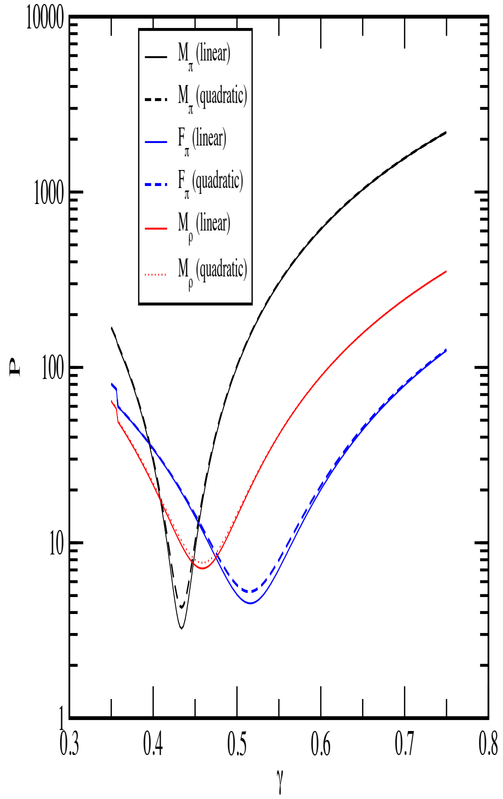

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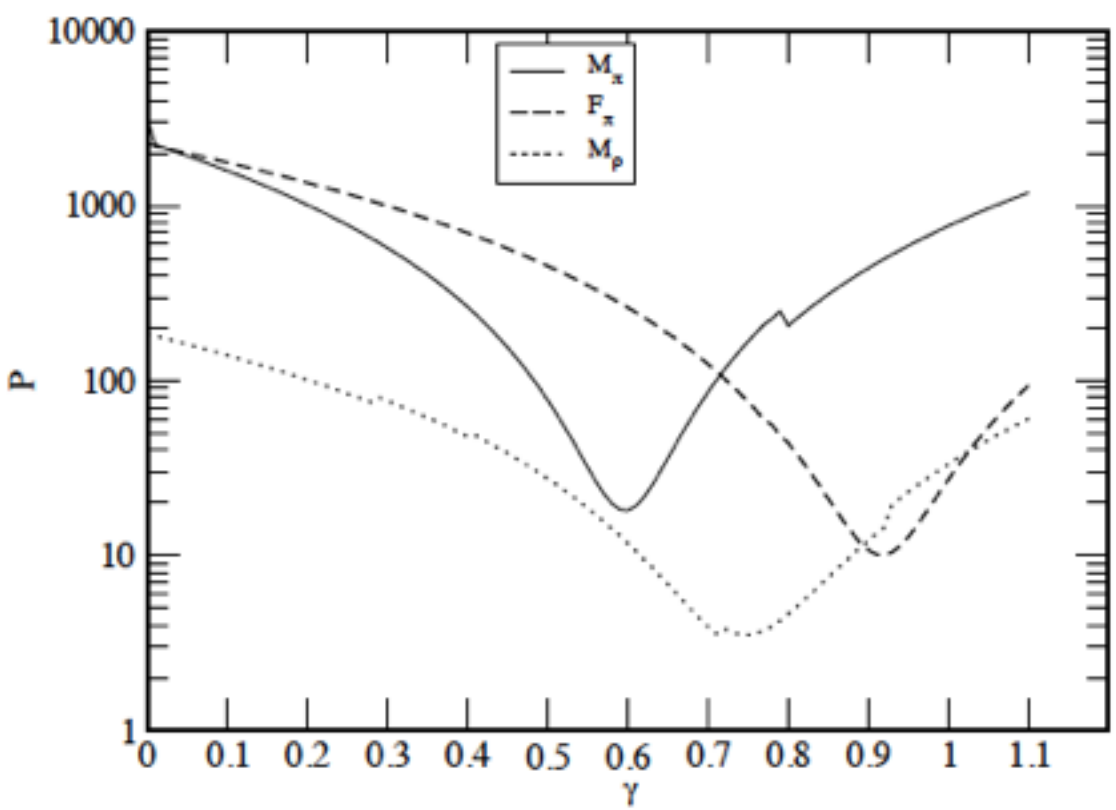
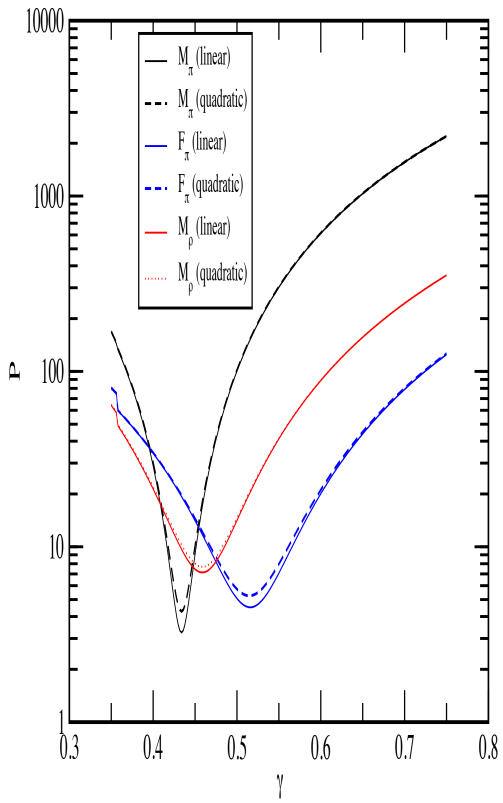


- Optimal γ obtained for each quantity
- γ scattered→no exact conformality

$P(\gamma)$ analysis for Nf=8



Nf=12

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M_π	0.434(4)
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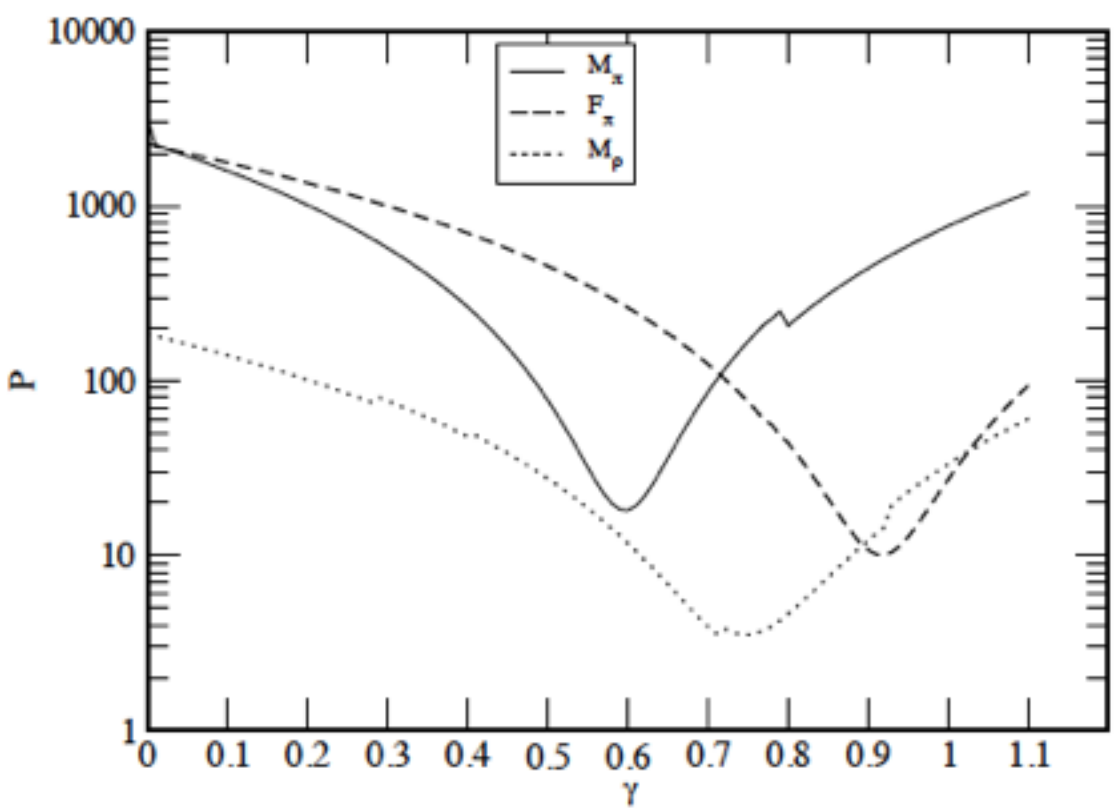
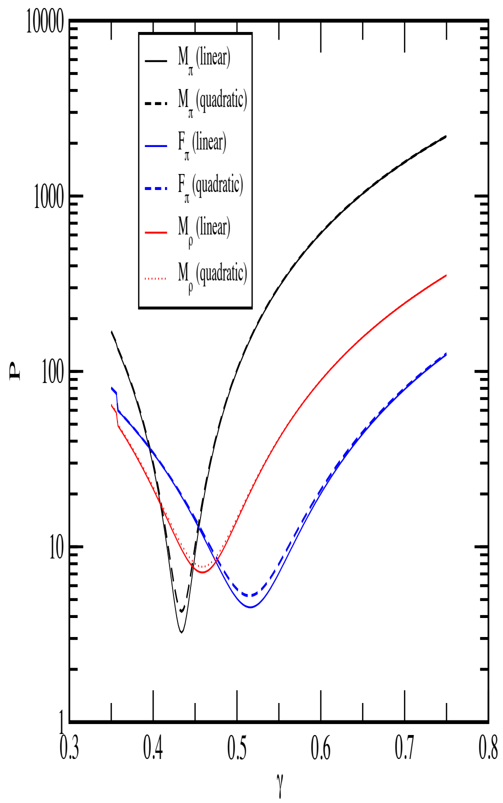


- Optimal γ obtained for each quantity
- γ scattered→no exact conformality
- scaling→remnant conformality

$P(\gamma)$ analysis for Nf=8



Nf=12

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statistical error only

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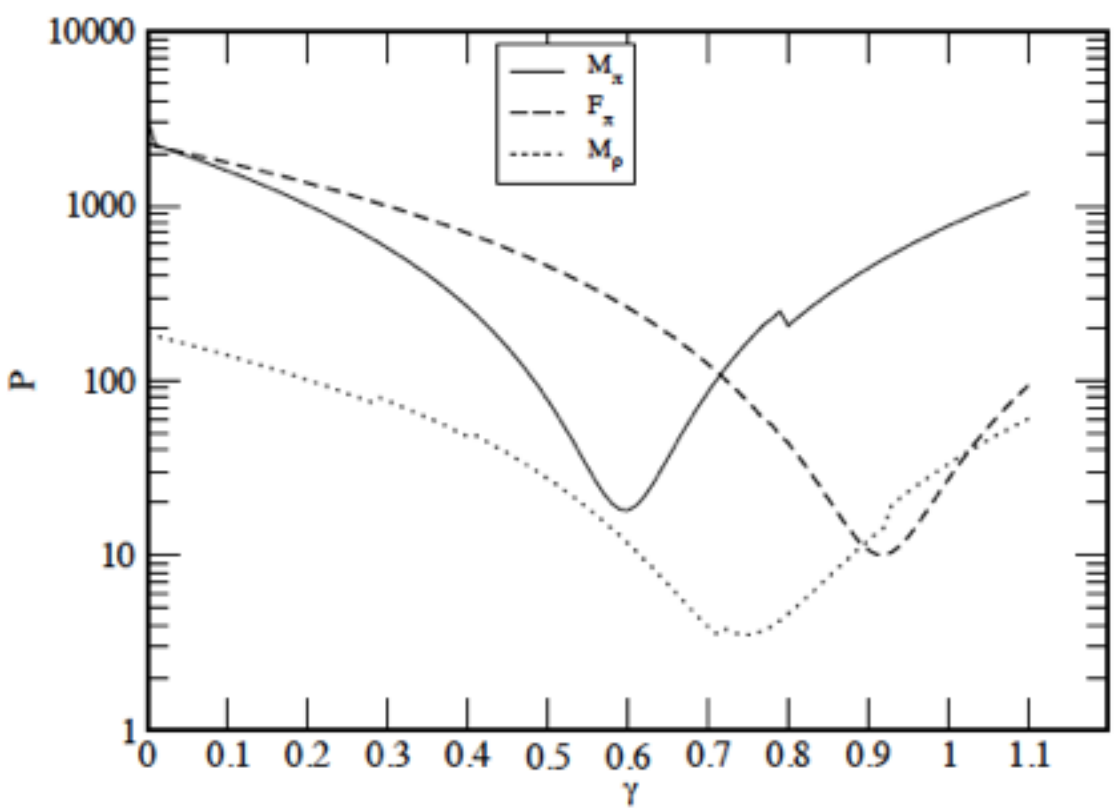

- Optimal γ obtained for each quantity
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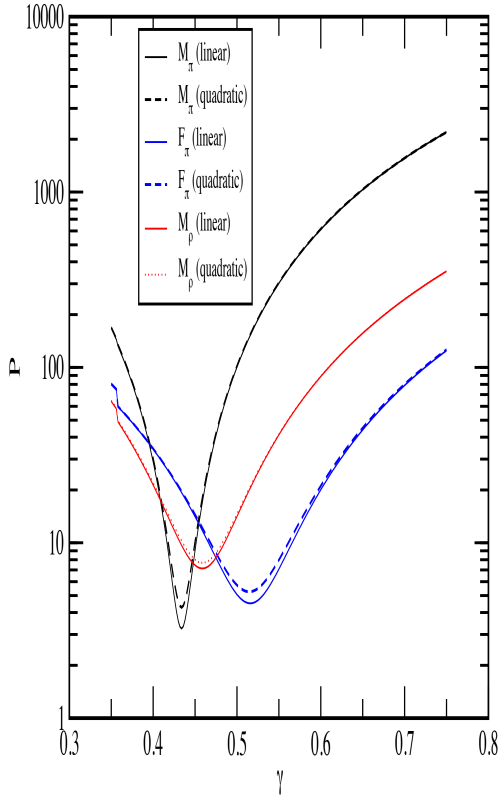
- remember: ~~chiral symmetry~~

$P(\gamma)$ analysis for N_f=8



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quantity	r
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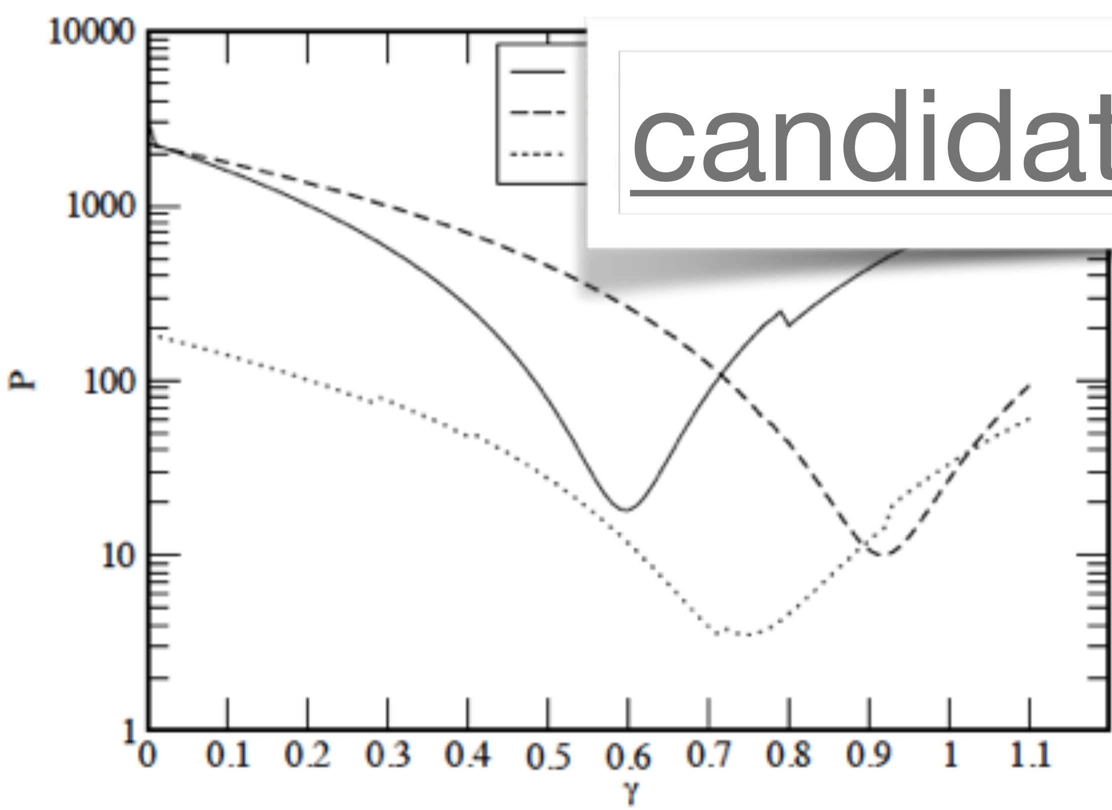
	5(4)
	(20)



candidate of walking TC

- Optimal γ obtained for each quantity
- γ scattered→no exact conformality
- scaling→remnant conformality
- remember: ~~chiral symmetry~~

TABLE VII. Summary of the optimal values of γ. See the text for details.

quantity	β	all
M_π	3.7	0.434(4)
F_π	3.7	0.516(12)
M_ρ	3.7	0.459(8)

TABLE VII. Summary of the optimal values of γ. See the text for details.

quantity	β	all	x: range 1	range 2	range 3
M_π	3.7	0.434(4)	0.425(9)	0.436(6)	0.437(4)
F_π	3.7	0.516(12)	0.481(19)	0.512(19)	0.544(14)
M_ρ	3.7	0.459(8)	0.411(17)	0.461(10)	0.473(8)

TABLE VII. Summary of the optimal values of γ. See the text for details.

			x		
quantity	β	all	range 1	range 2	range 3
M_π	3.7	0.434(4)	0.425(9)	0.436(6)	0.437(4)
F_π	3.7	0.516(12)	0.481(19)	0.512(19)	0.544(14)
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- β=3.7: smaller m : closer to M_π

TABLE VII. Summary of the optimal values of γ. See the text for details.

			x			L		
quantity	β	all	range 1	range 2	range 3	(18,24)	(18,30)	(24,30)
M_π	3.7	0.434(4)	0.425(9)	0.436(6)	0.437(4)	0.438(6)	0.433(4)	0.429(8)
F_π	3.7	0.516(12)	0.481(19)	0.512(19)	0.544(14)	0.526(18)	0.514(11)	0.505(24)
M_ρ	3.7	0.459(8)	0.411(17)	0.461(10)	0.473(8)	0.491(15)	0.457(8)	0.414(18)

- β=3.7: smaller m : closer to M_π

TABLE VII. Summary of the optimal values of γ. See the text for details.

			x			L		
quantity	β	all	range 1	range 2	range 3	(18,24)	(18,30)	(24,30)
M_π	3.7	0.434(4)	0.425(9)	0.436(6)	0.437(4)	0.438(6)	0.433(4)	0.429(8)
F_π	3.7	0.516(12)	0.481(19)	0.512(19)	0.544(14)	0.526(18)	0.514(11)	0.505(24)
M_ρ	3.7	0.459(8)	0.411(17)	0.461(10)	0.473(8)	0.491(15)	0.457(8)	0.414(18)

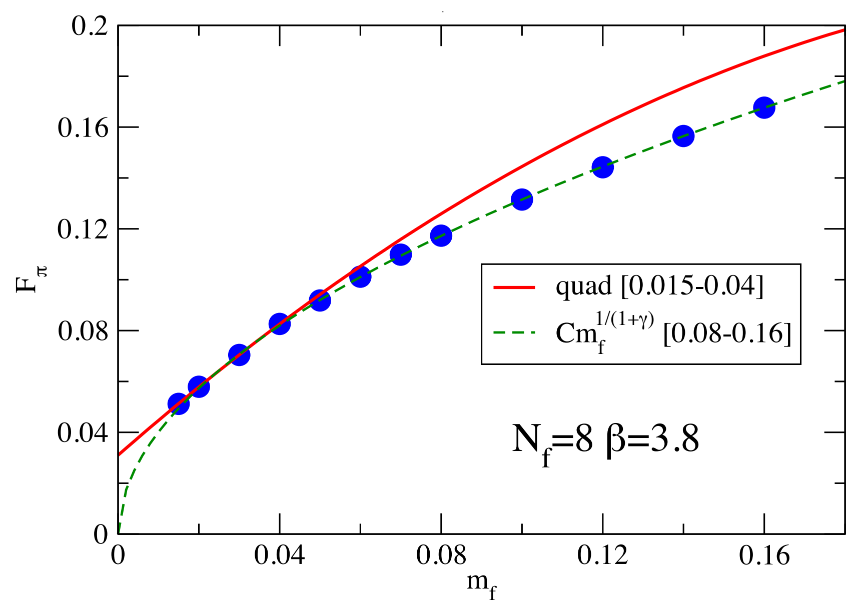
- β=3.7: smaller m : closer to M_π
- β=3.7: larger V: closer to M_π
-

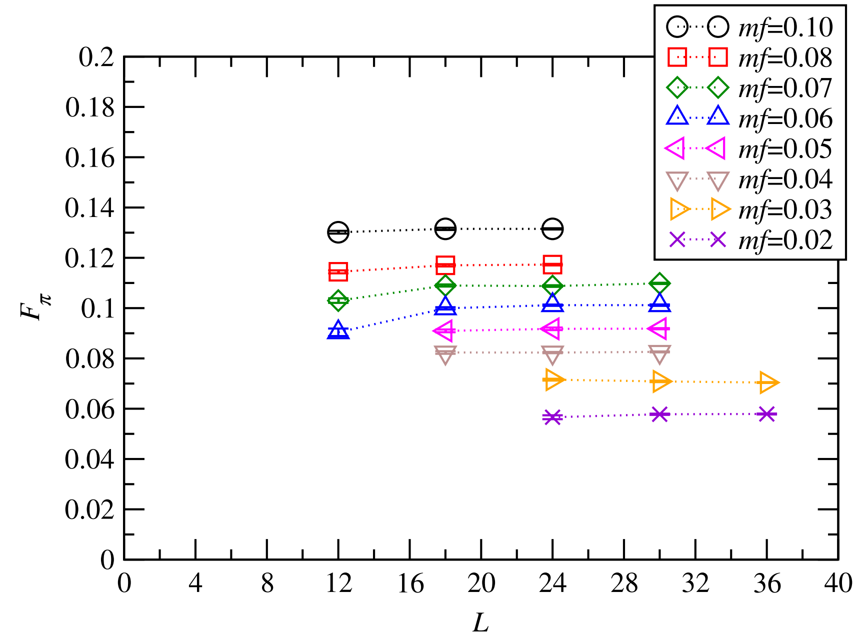
Nf=8: including smaller mf → scaling gets worse

$$F_\pi = C_1 m_f^{1/(1+\gamma)}$$

Fit range (m_f)	C_1	γ	χ^2/dof
0.015–0.04	0.415(7)	0.988(19)	14.8
0.015–0.05	0.414(5)	0.991(15)	9.84
0.015–0.06	0.418(4)	0.979(12)	7.88
0.015–0.07	0.424(3)	0.963(9)	7.35
0.015–0.08	0.425(3)	0.961(8)	6.15
0.015–0.10	0.426(2)	0.958(7)	5.31
0.015–0.16	0.428(1)	0.952(4)	3.98
0.02–0.16	0.429(1)	0.947(4)	2.22
0.03–0.16	0.431(1)	0.942(5)	1.94
0.04–0.16	0.429(2)	0.950(10)	1.23
0.05–0.16	0.431(2)	0.941(7)	0.66
0.06–0.16	0.429(2)	0.948(9)	0.44
0.07–0.16	0.429(3)	0.950(10)	0.52
0.08–0.16	0.431(3)	0.939(14)	0.20
0.10–0.16	0.432(4)	0.934(19)	0.23

$N_f=8$





N_f=8: an interpretation

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  - hyperscaling for intermediate m_f
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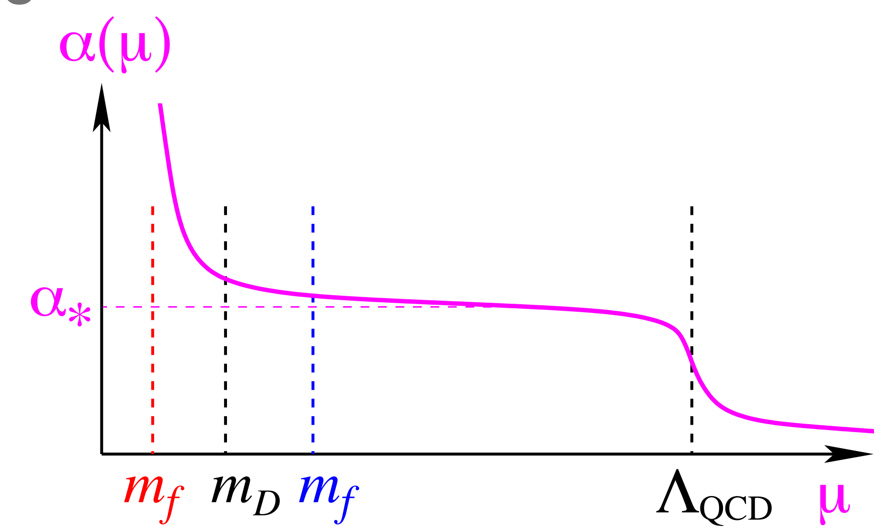

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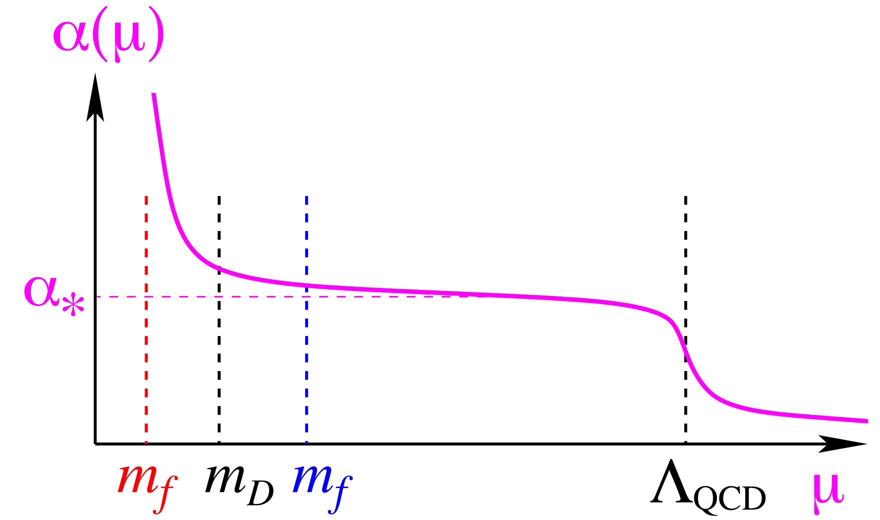

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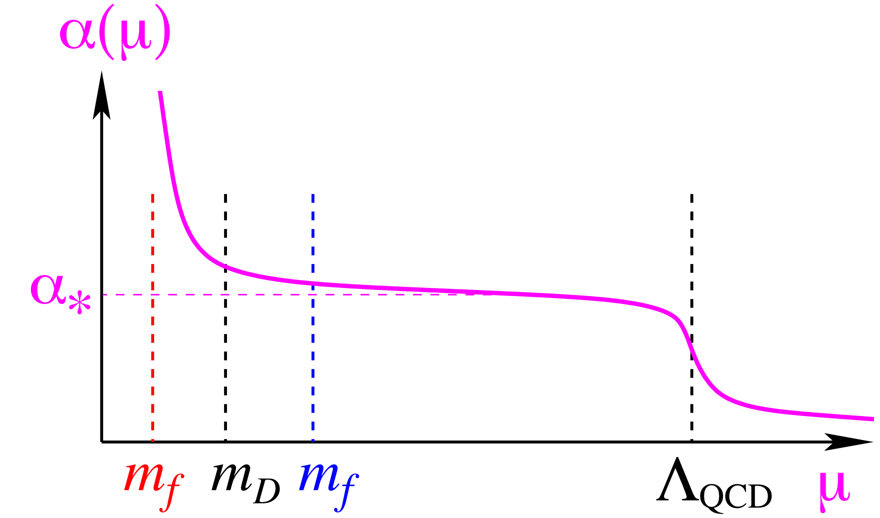

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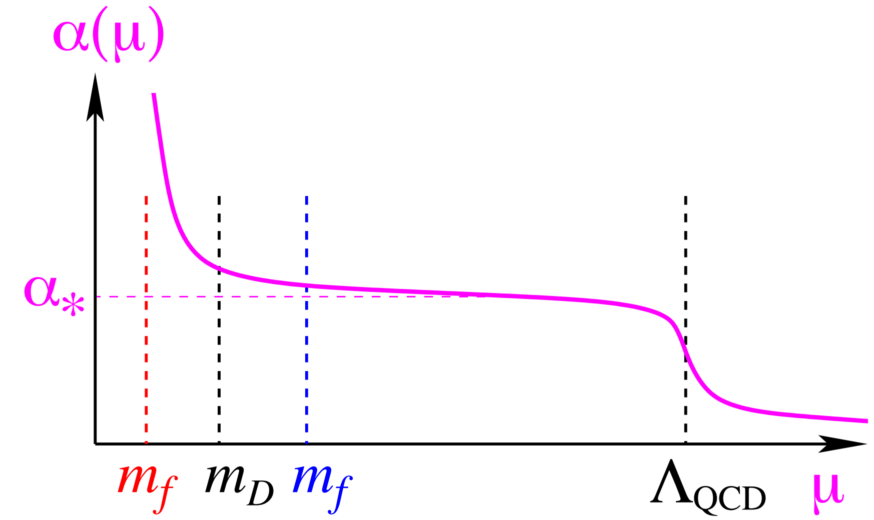


- walking: a solution to classical technicolor problem: quark mass $\leftrightarrow$ FCNC
- Next interesting direction $\to$ prediction (postdiction) of spectrum

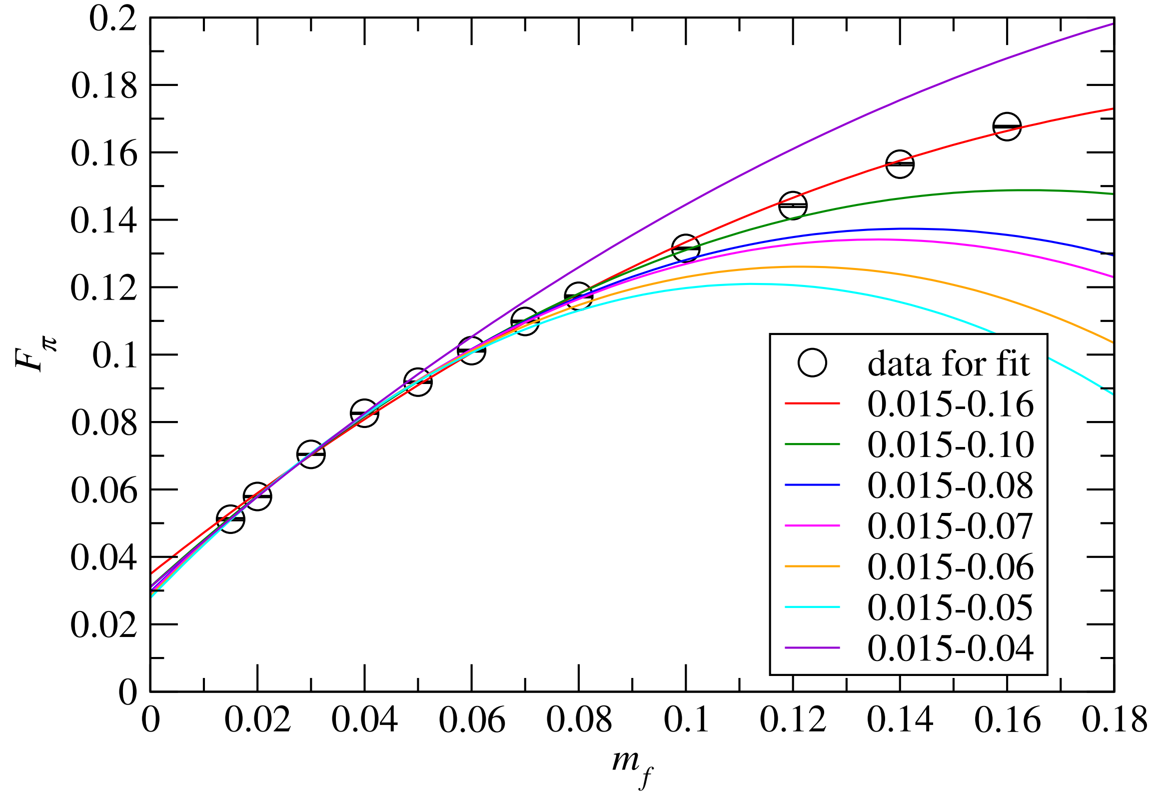


FIG. 8 (color online). Results of quadratic fit of F_π for various fit ranges.

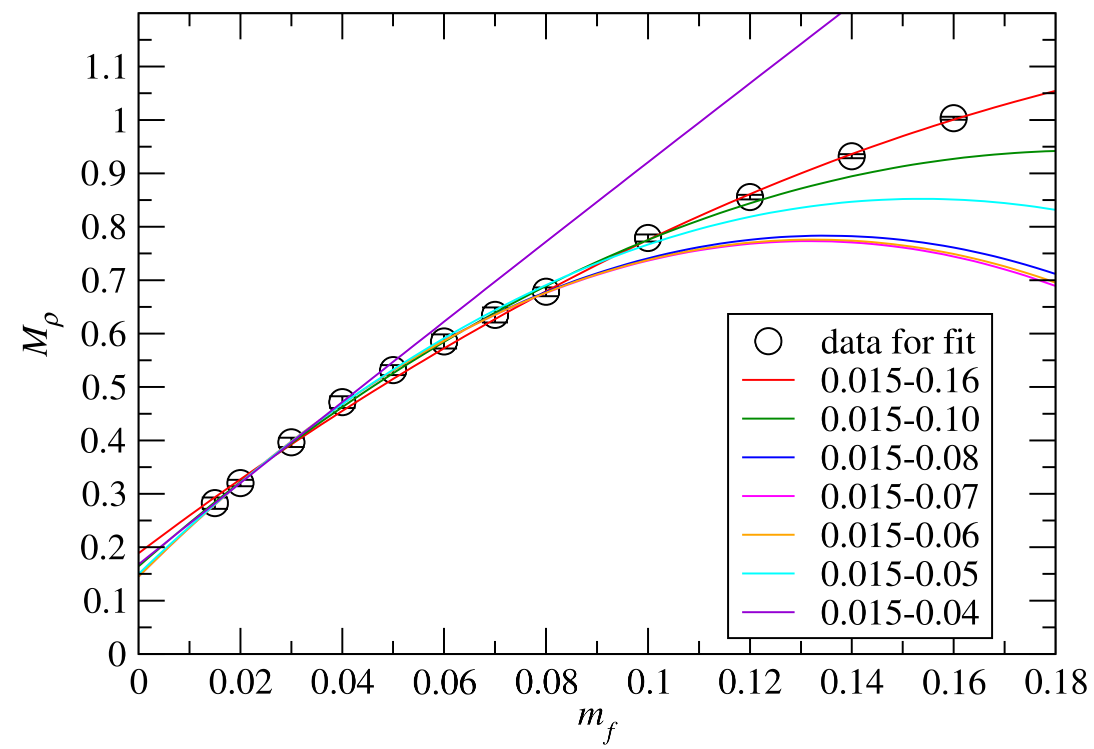


FIG. 9 (color online). Results of quadratic fit of M_ρ for various fit ranges.

$$F = 0.031(1)\binom{+2}{-10},$$

$$M_\rho = 0.168(32).$$

- chiral log correction included in the systematic error of F

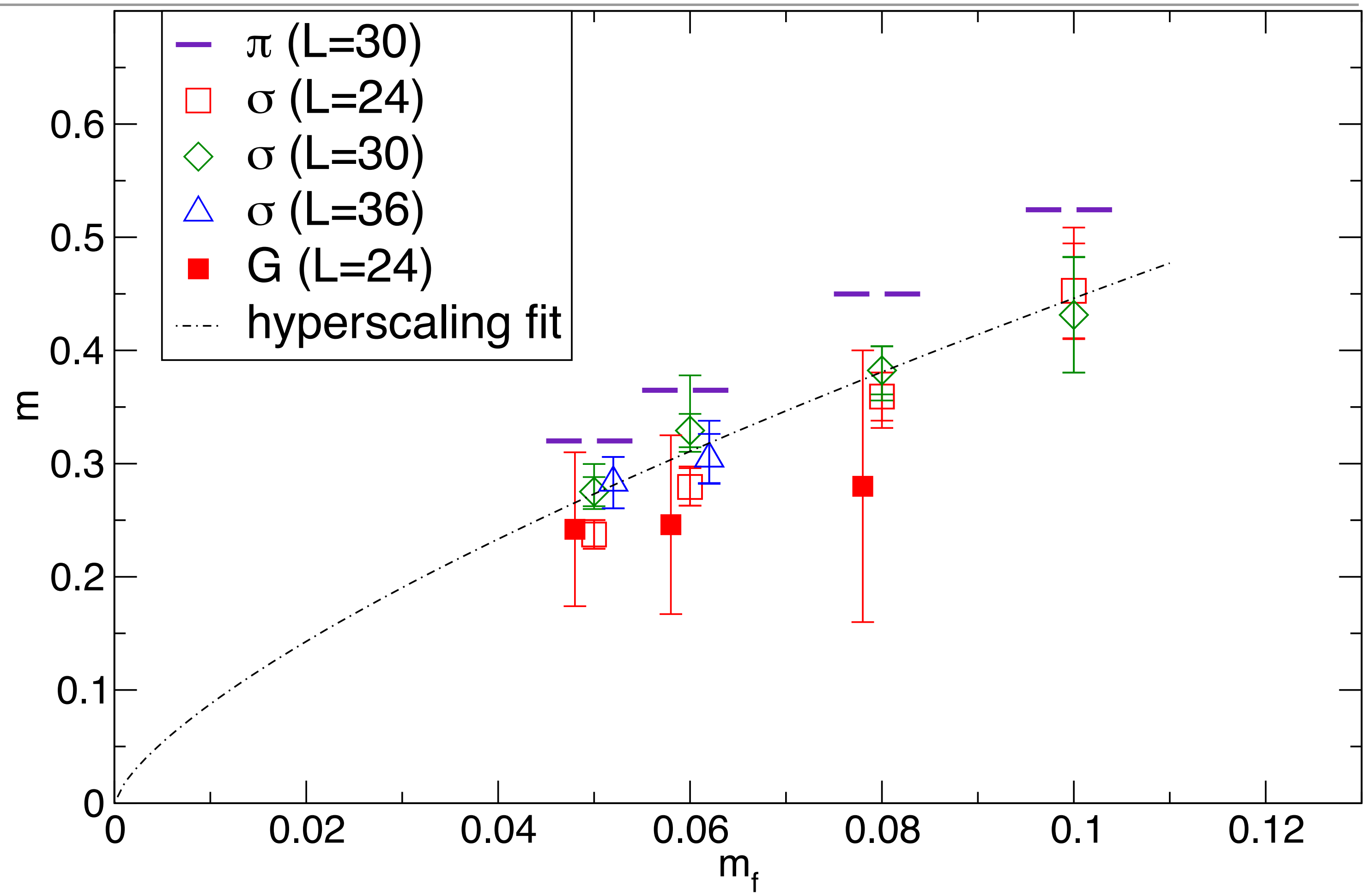
N_f=8 spectrum

- with input F_π = 246 /√N GeV   (N: # weak doublet in techni-sector)
- prediction: $M_\rho/F_\pi = 7.7(1.5)(^{+3.8}_{-0.4})$ (with only technicolor dynamics)
    - for example: $M_\rho = 970(^{+515}_{-195})\ \mathrm{GeV}$ for one family model: N=4
- Higgs mass ?
    - 125 GeV (LHC) seems very light for technicolor
    - 0++: one of the difficult quantities on the lattice
    - multi-faceted nature of N_f=8 adds another difficulty: delicate chiral extrapl.

➡ first analyze simpler N_f=12, which shares “conformality” → techni dilaton

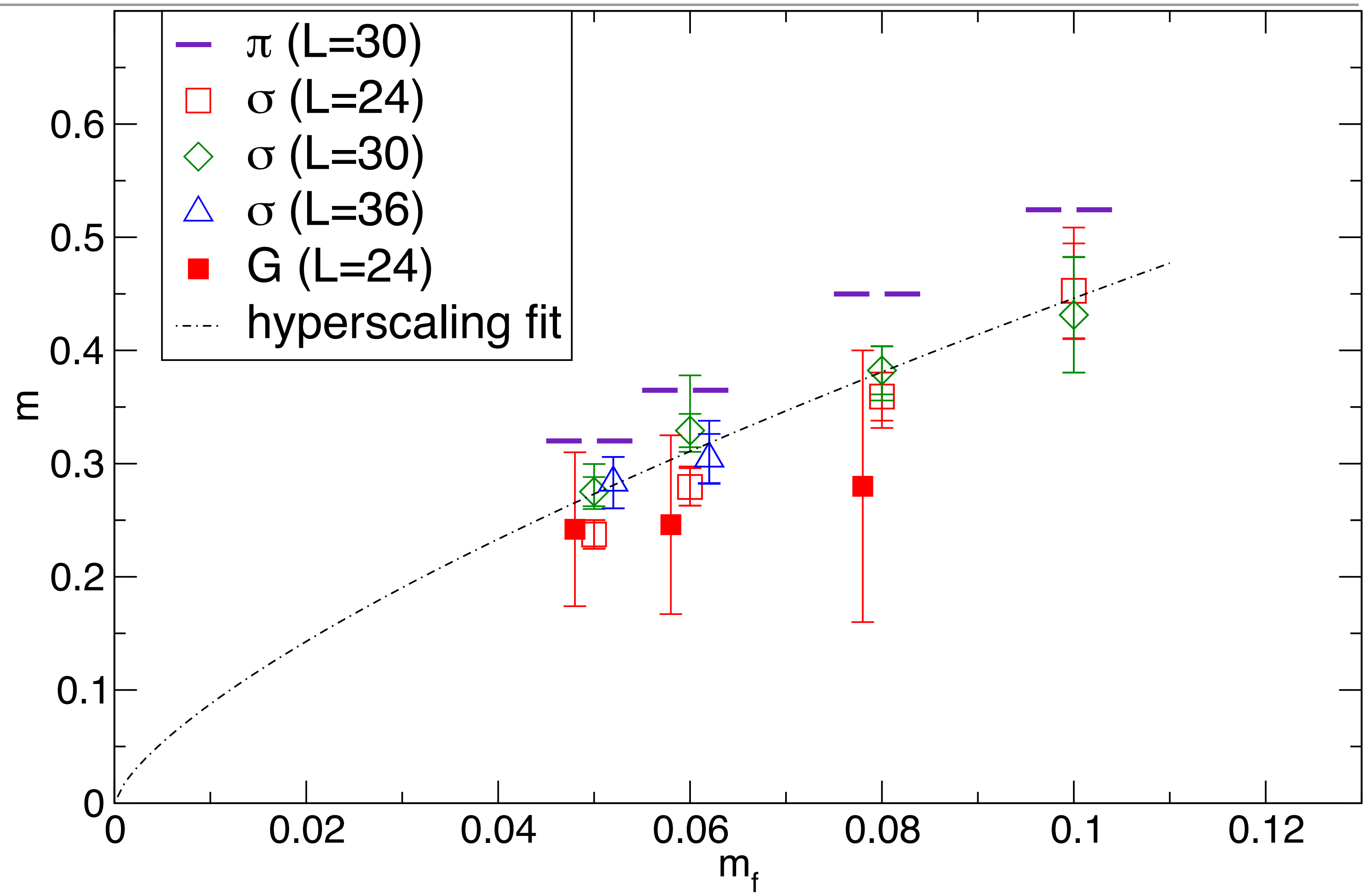
➡Is 0++ state light in (mass deformed) N_f=12 theory ?

flavor singlet scalar spectrum in Nf=12 theory



flavor singlet scalar spectrum in Nf=12 theory

- with very high statistics
- and a variance reduction
- we got a reasonable signal



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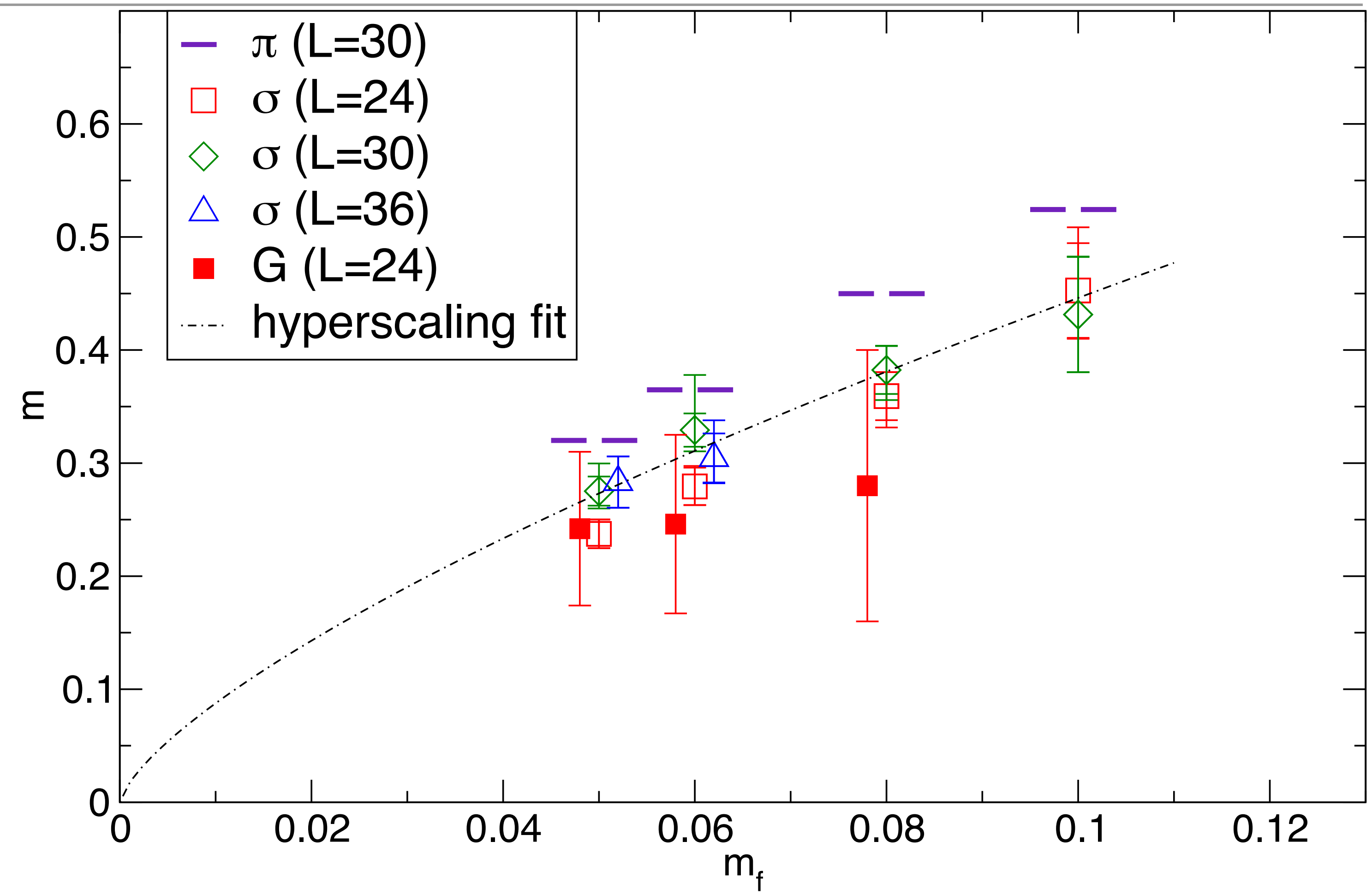

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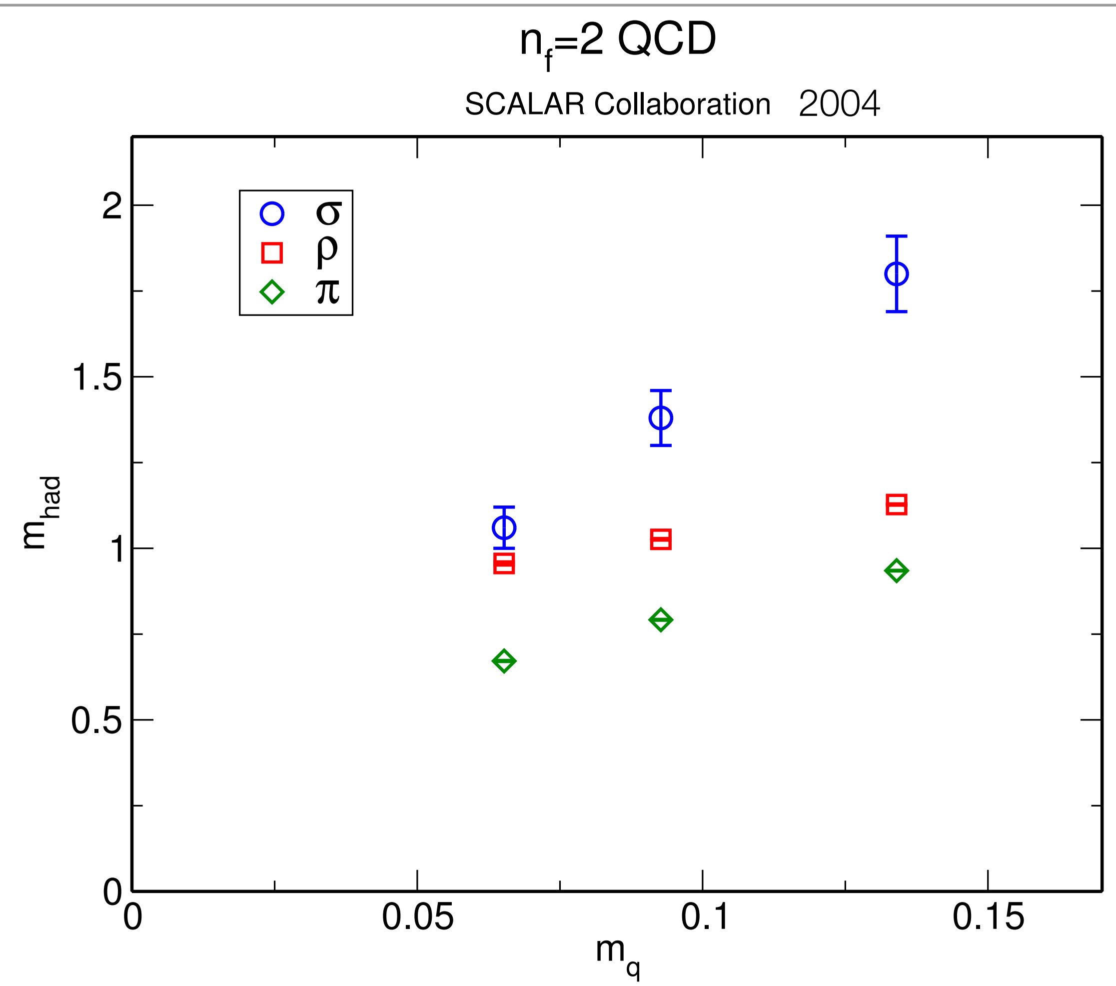

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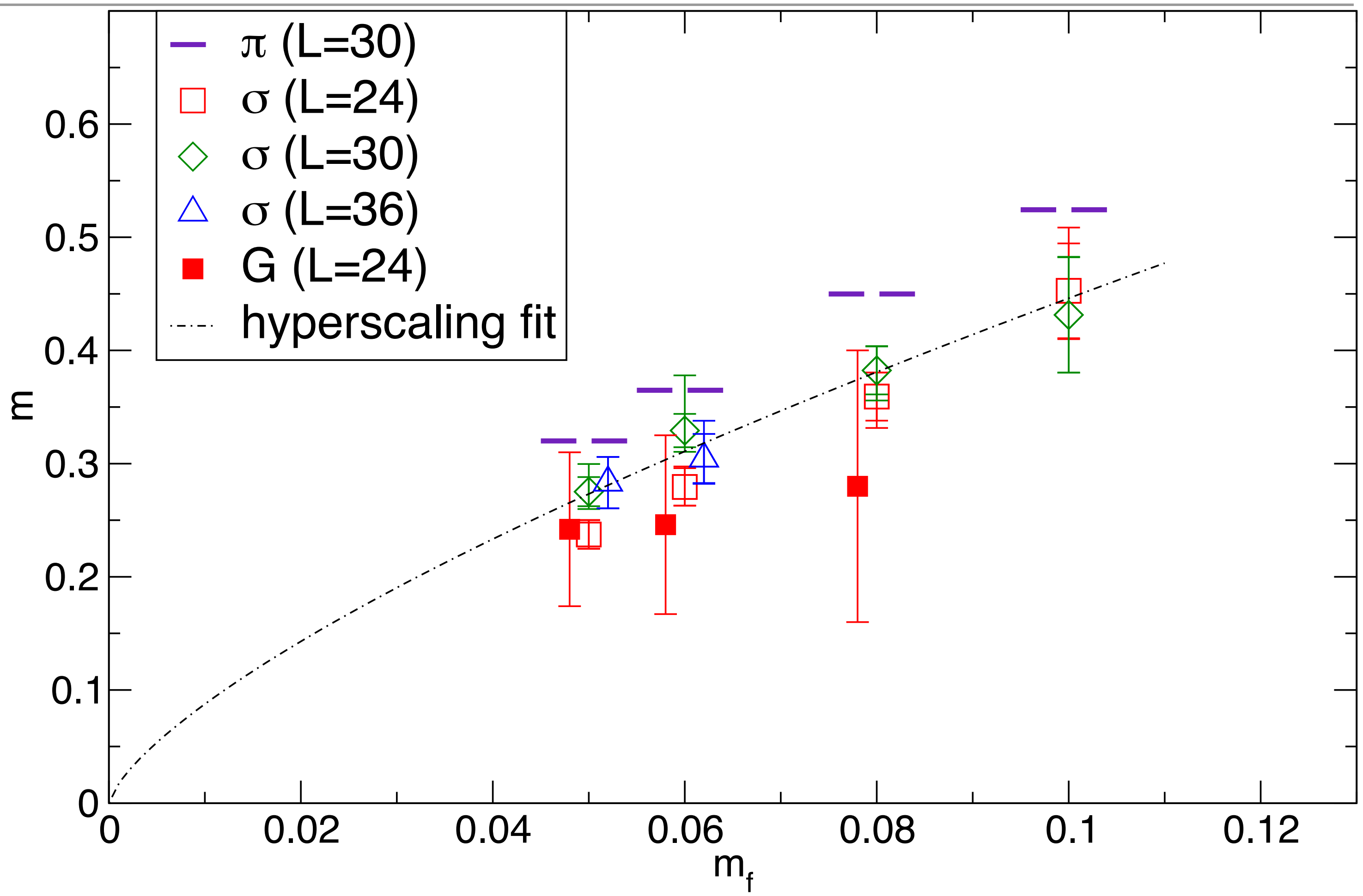

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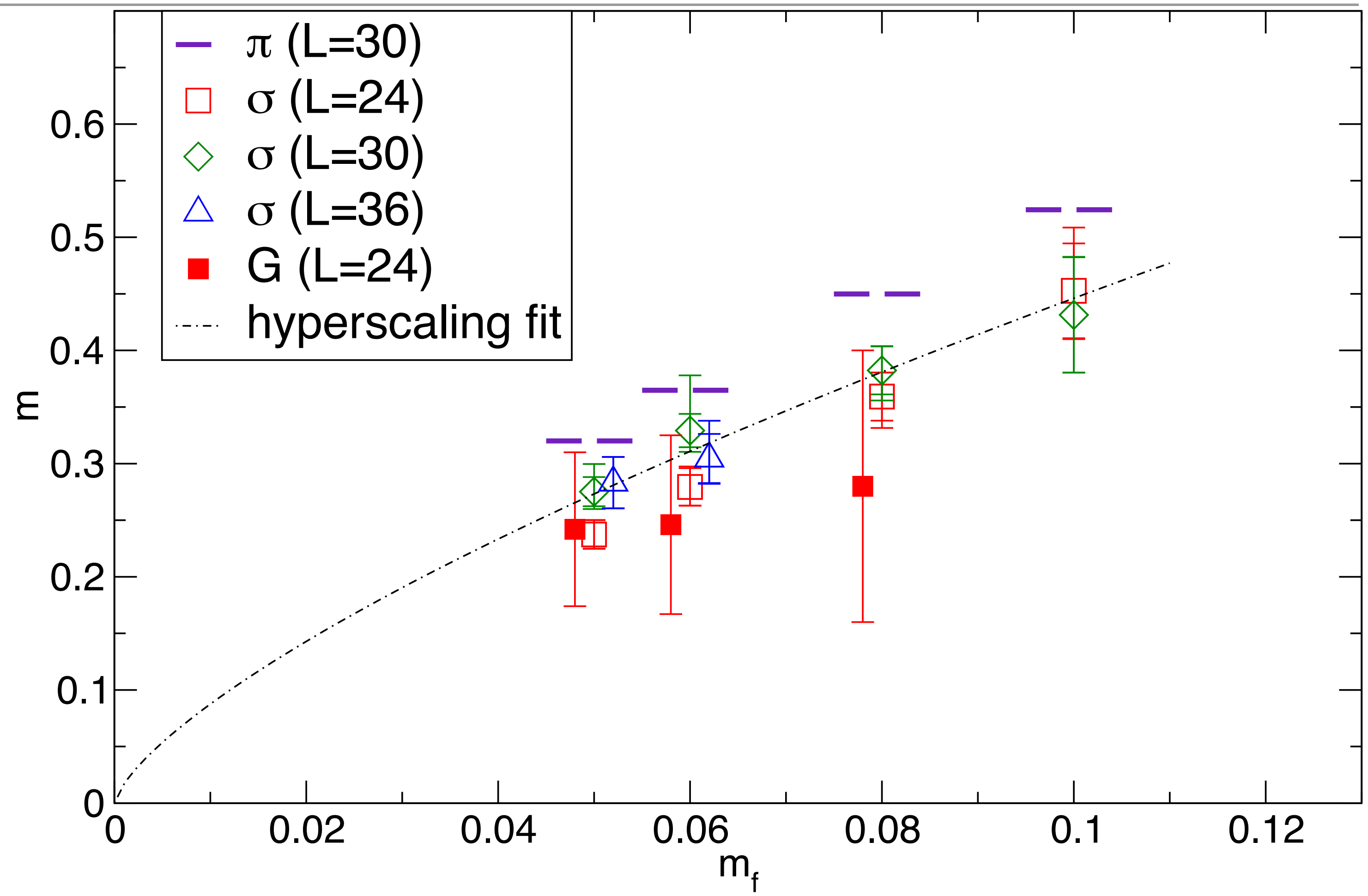

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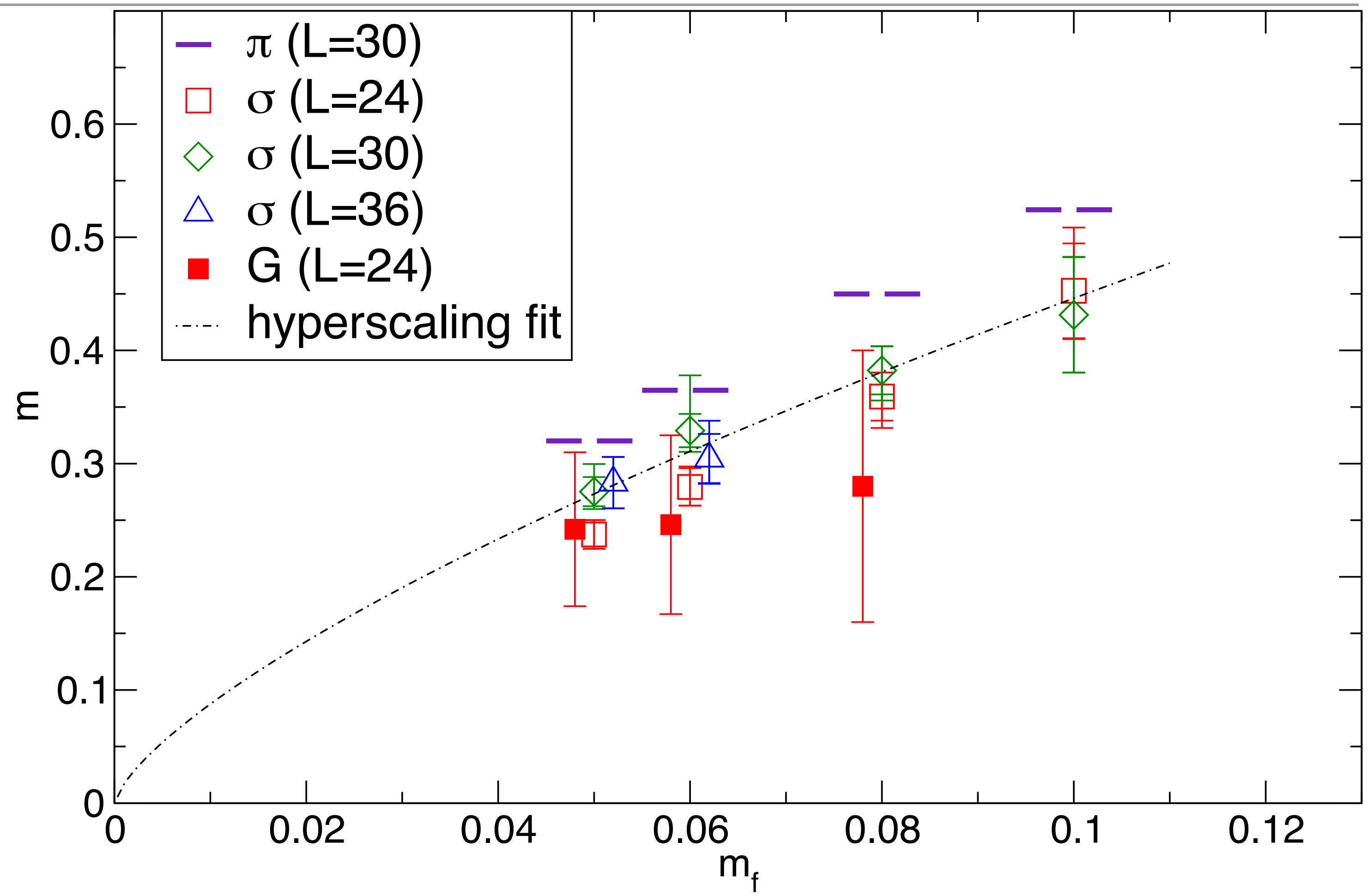

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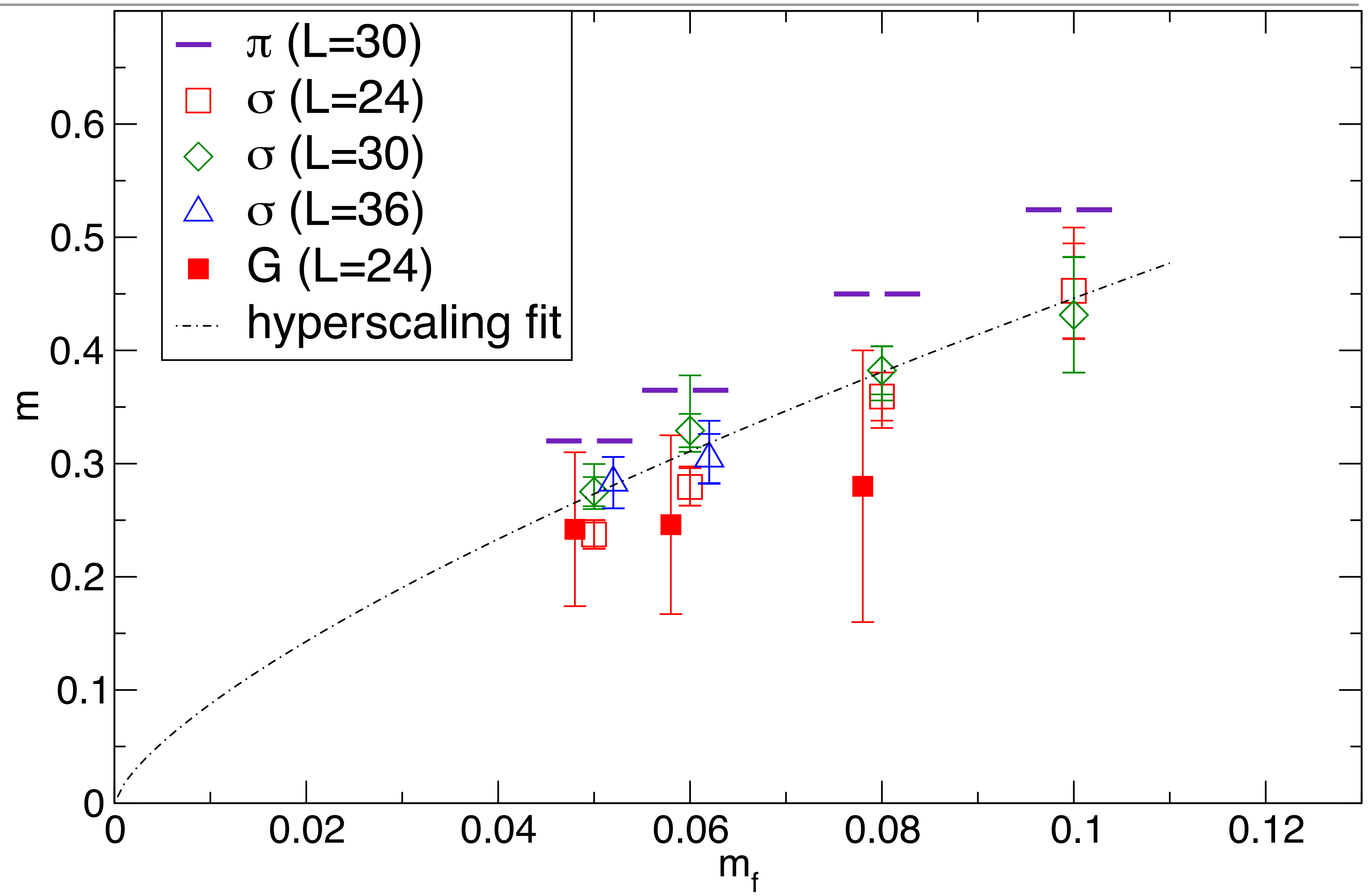

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- LatKMI, PRL 111 (2013), “Light composite scalar in twelve-flavor QCD on the lattice”

scalar (Higgs) in Nf=8 theory

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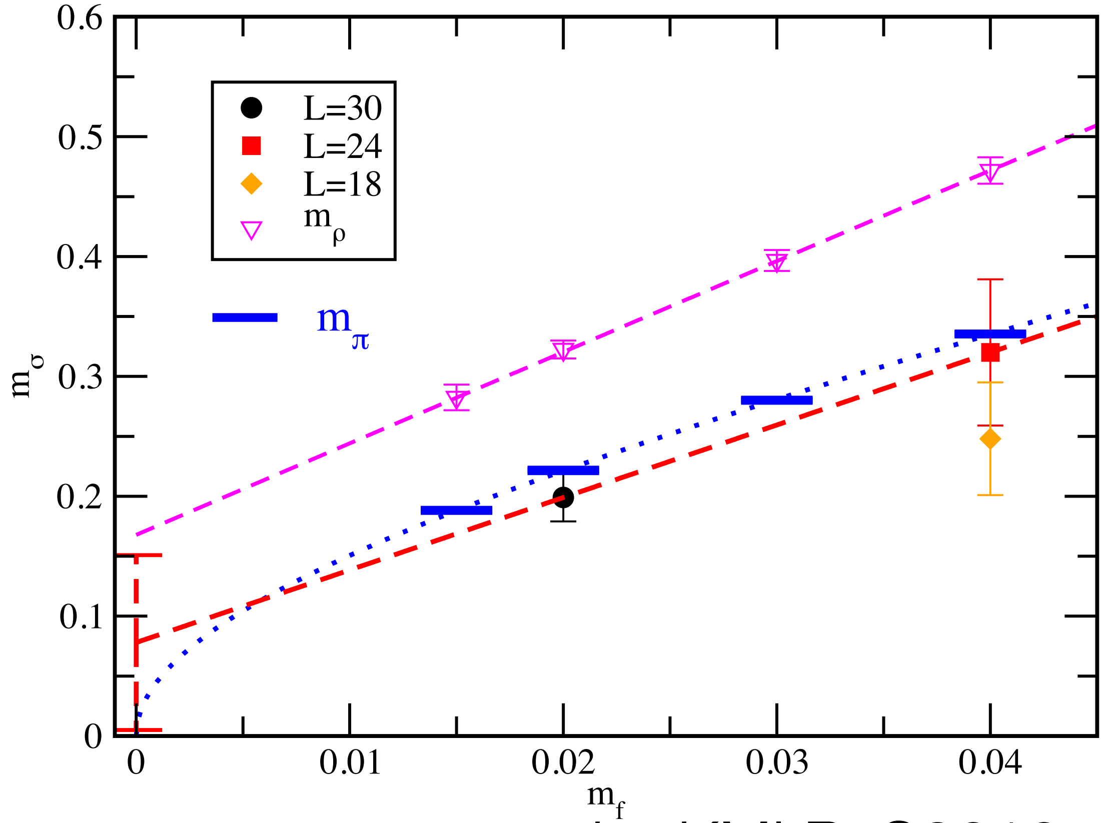

LatKMI PoS2013

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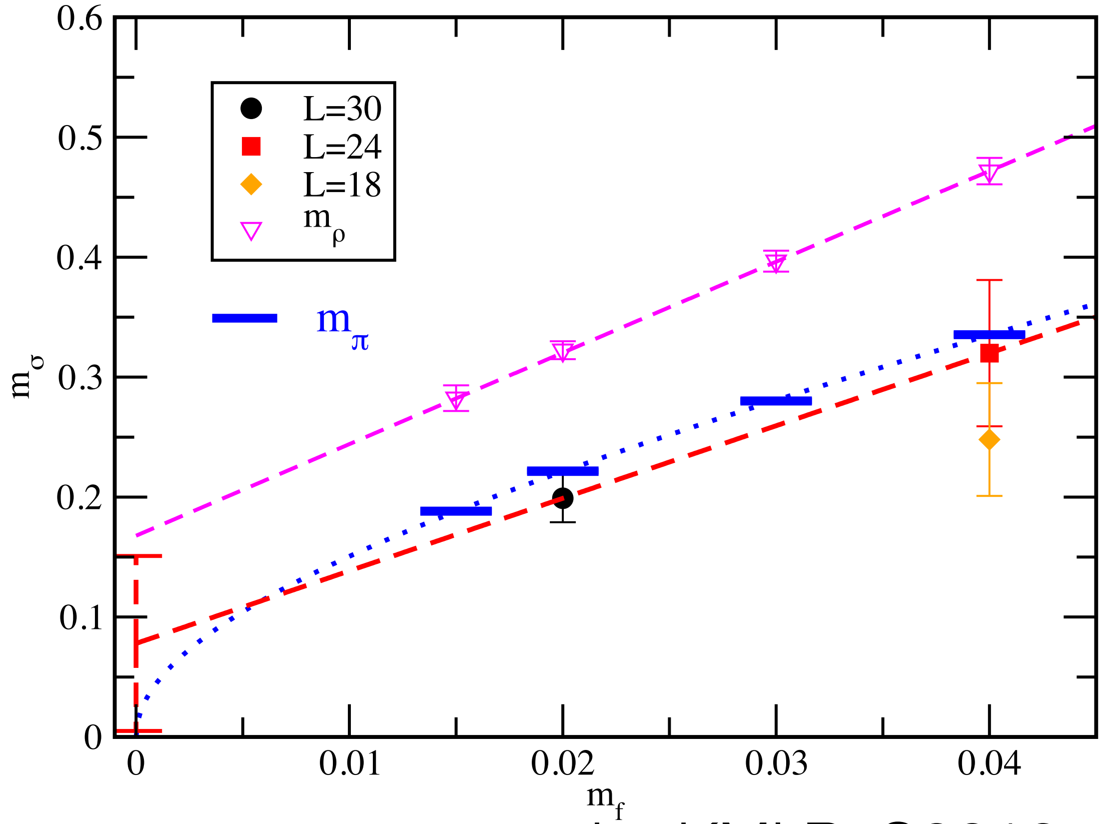

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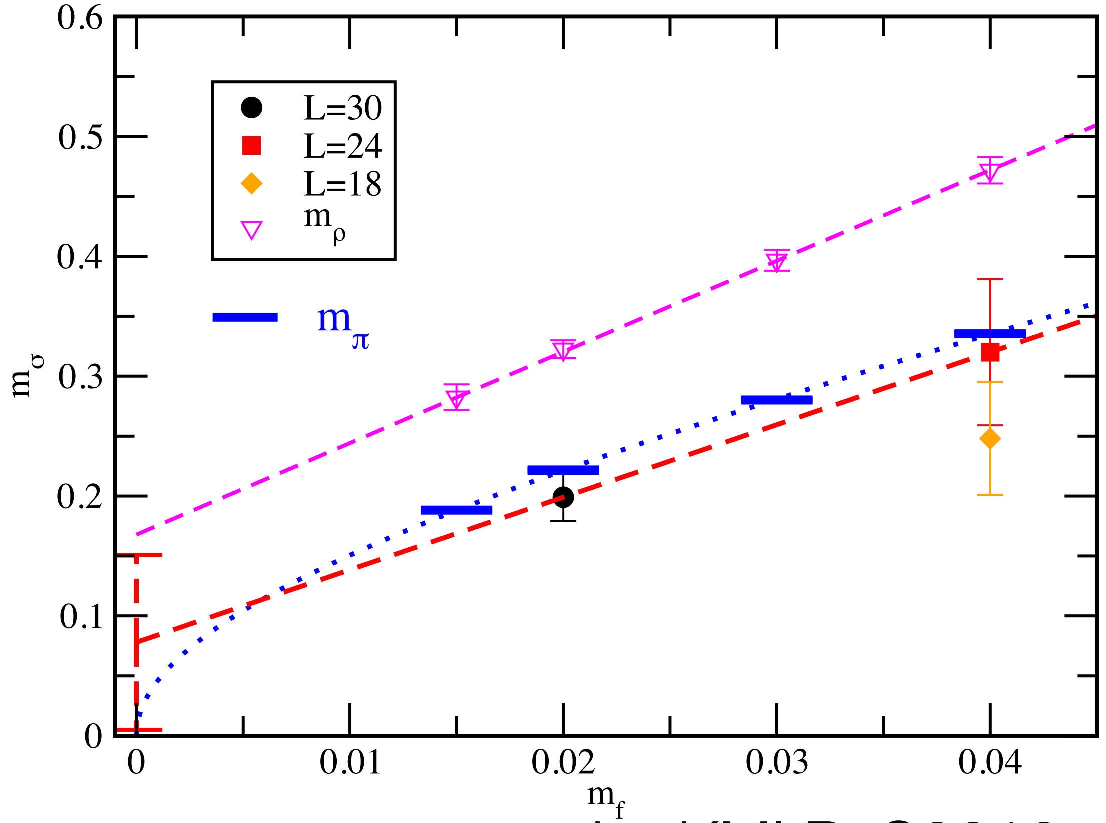

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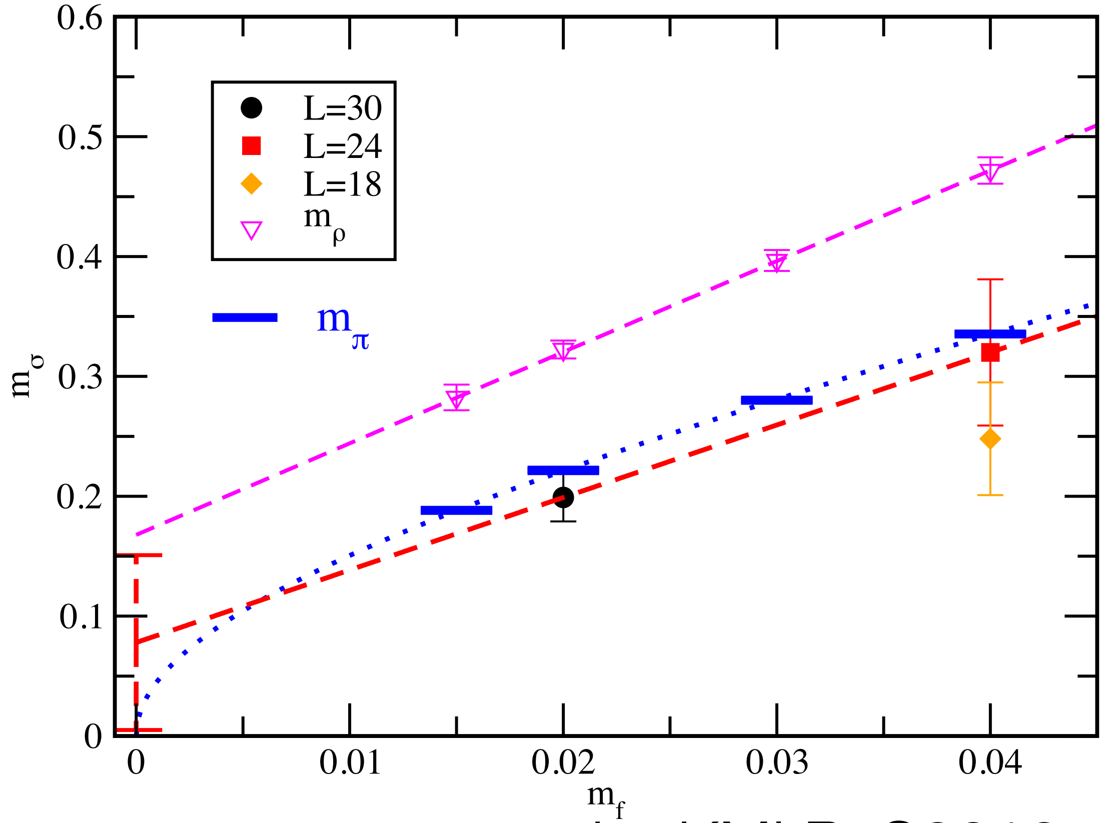

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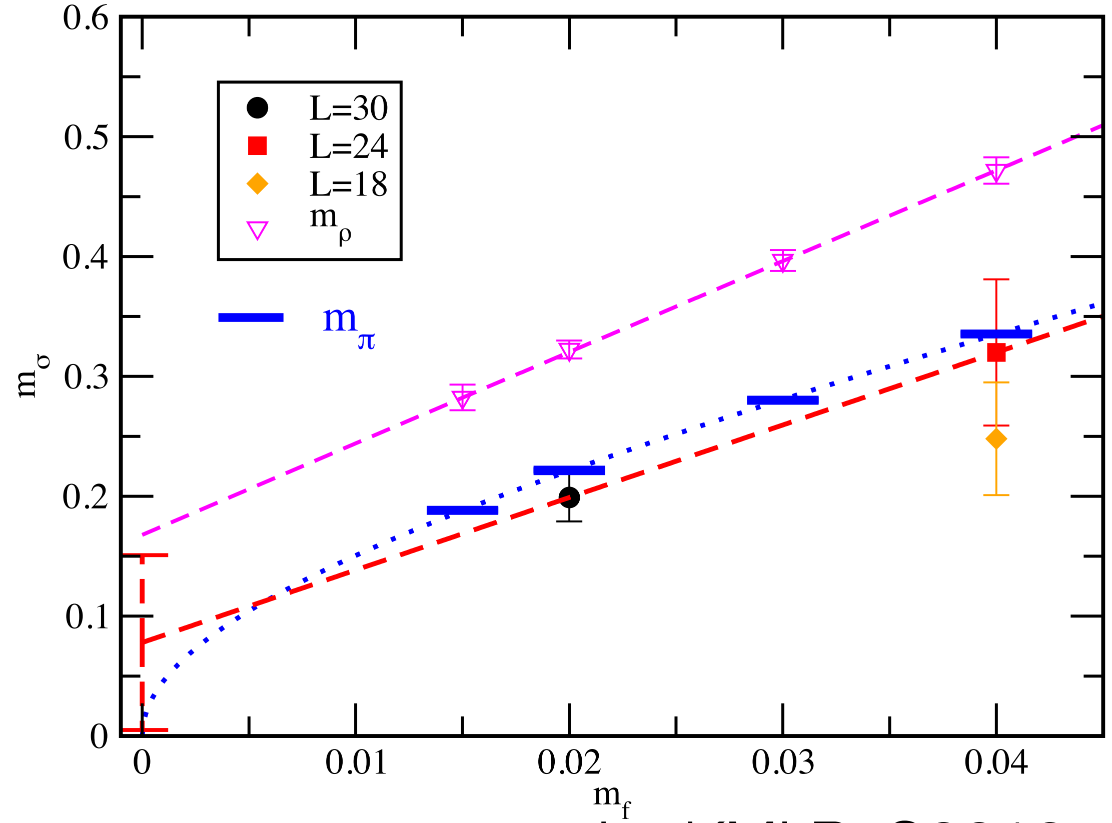

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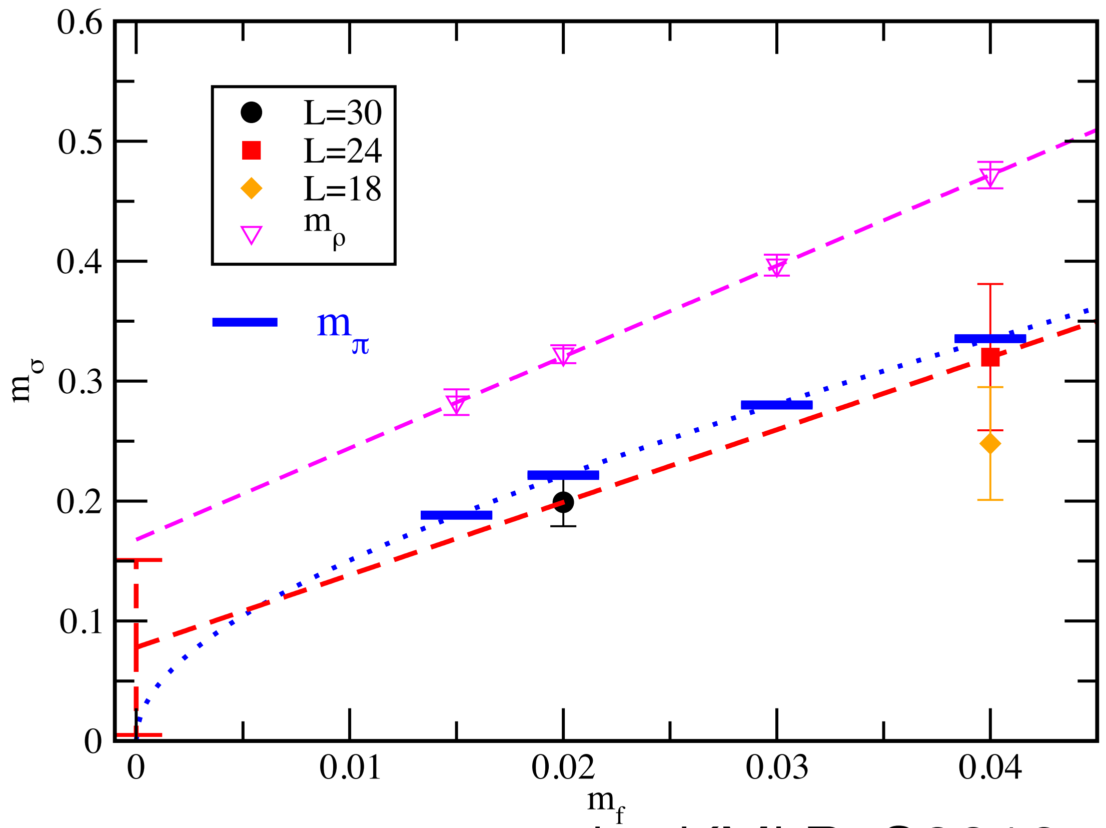

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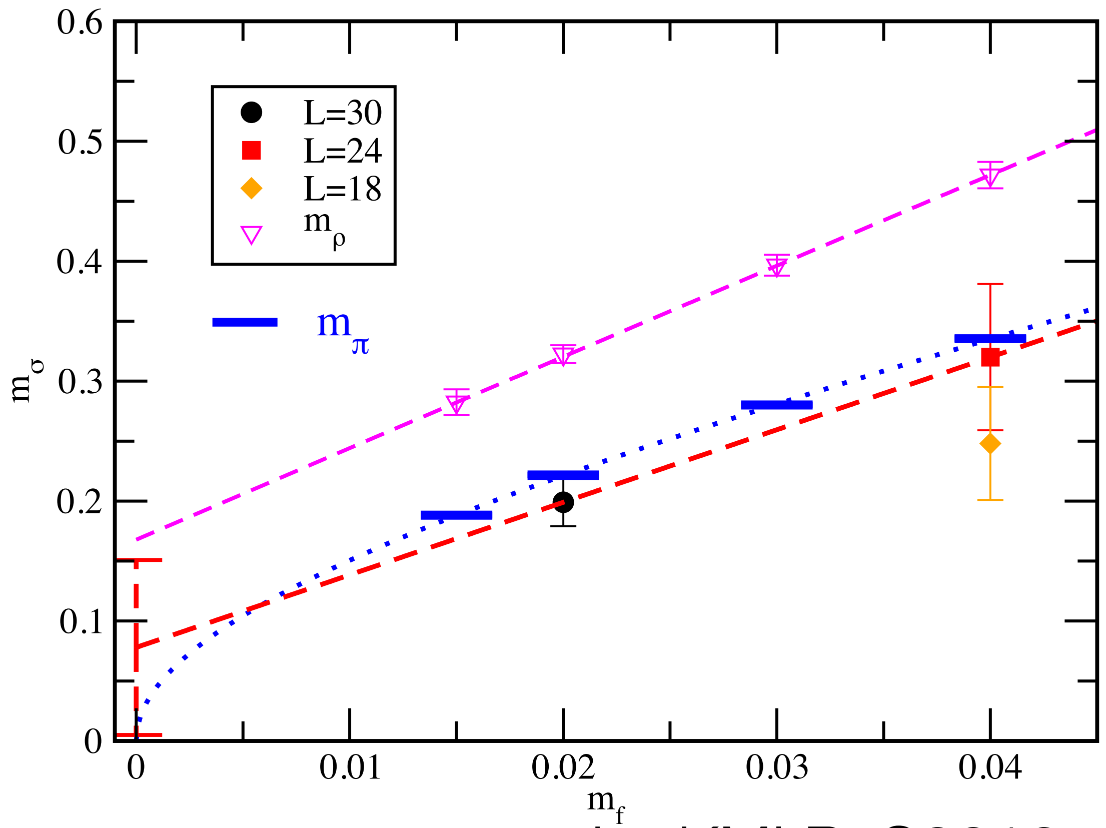

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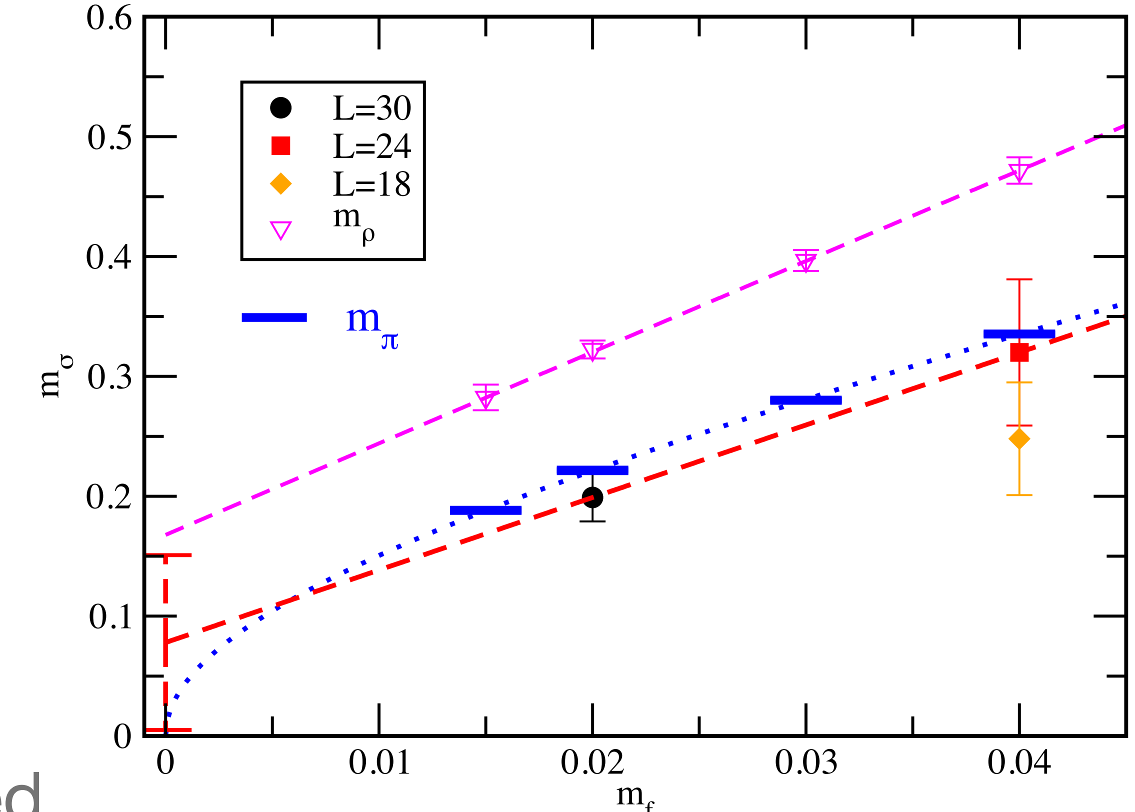

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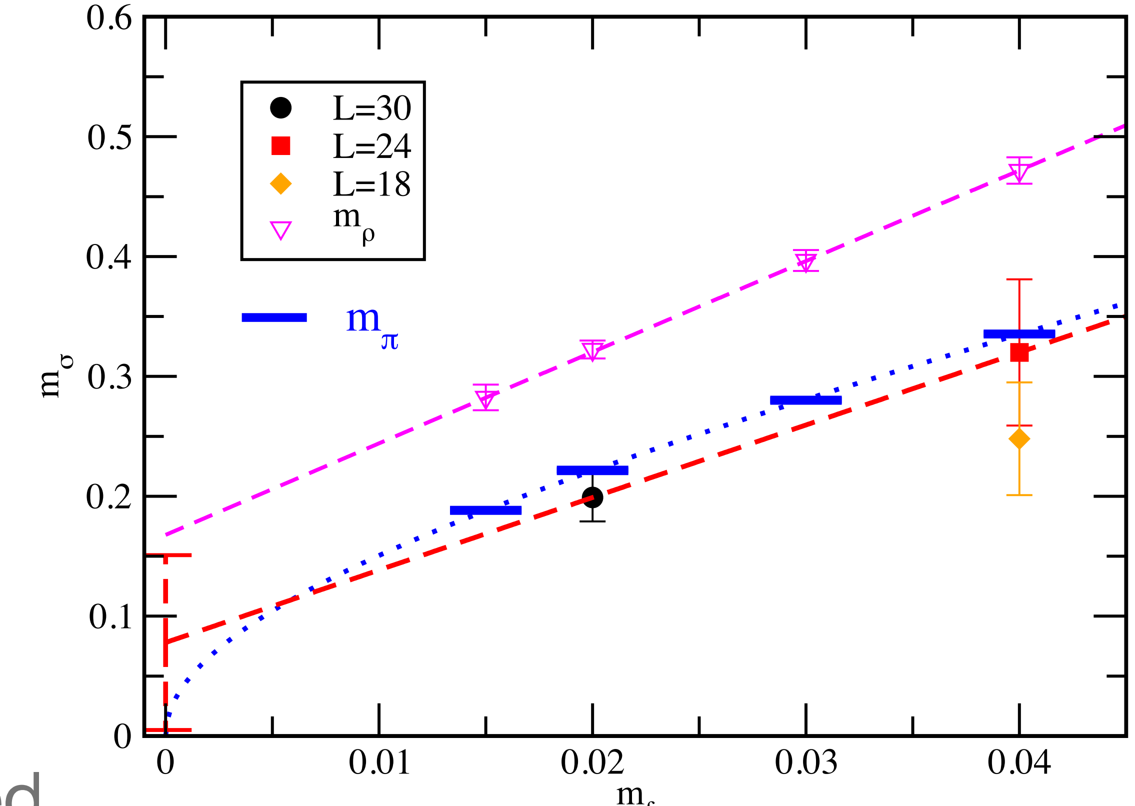

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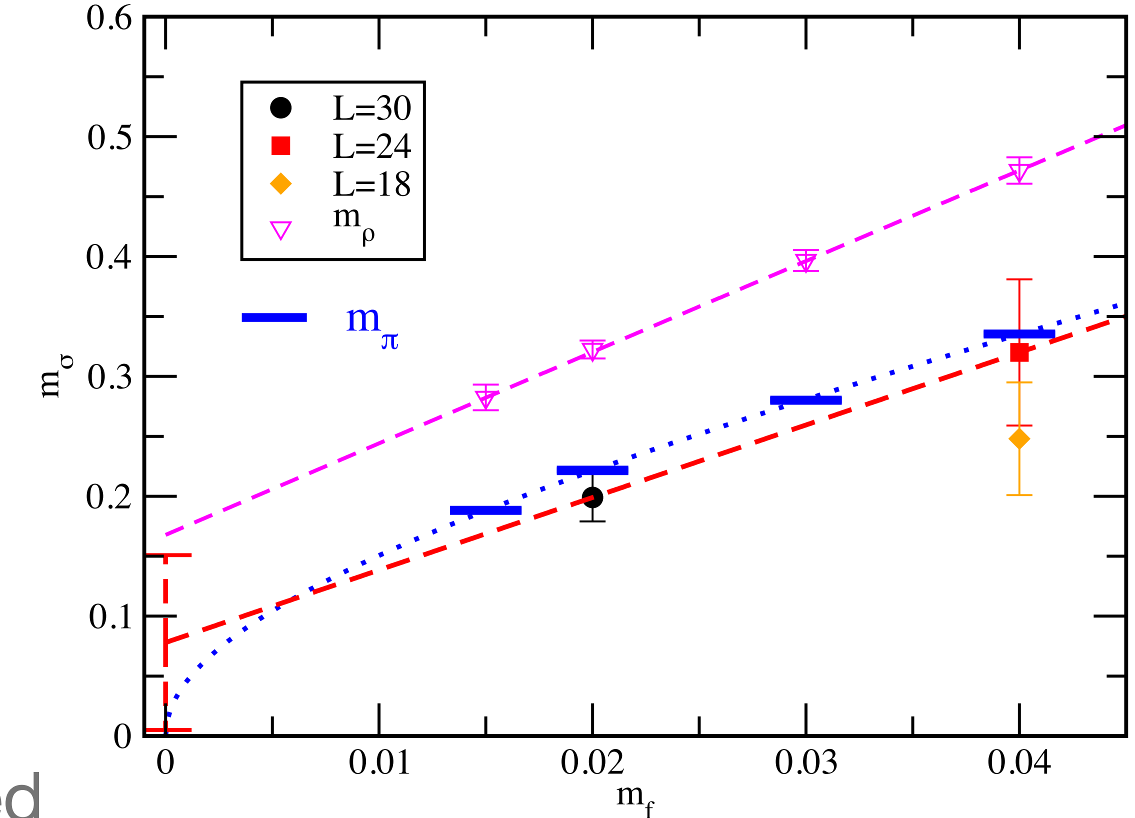
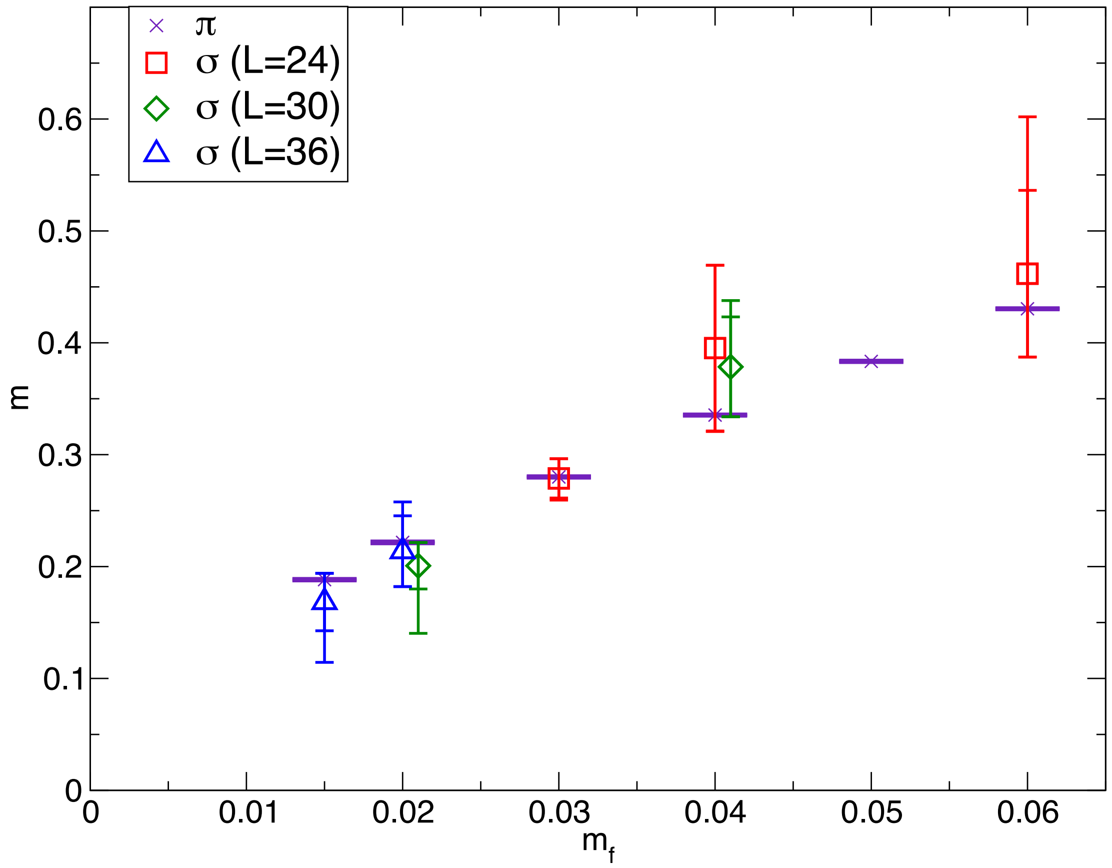
  - needs a change in chiral effective theory



LatKMI PoS2013

Nf=8 scalar: Update after Lattice 2013



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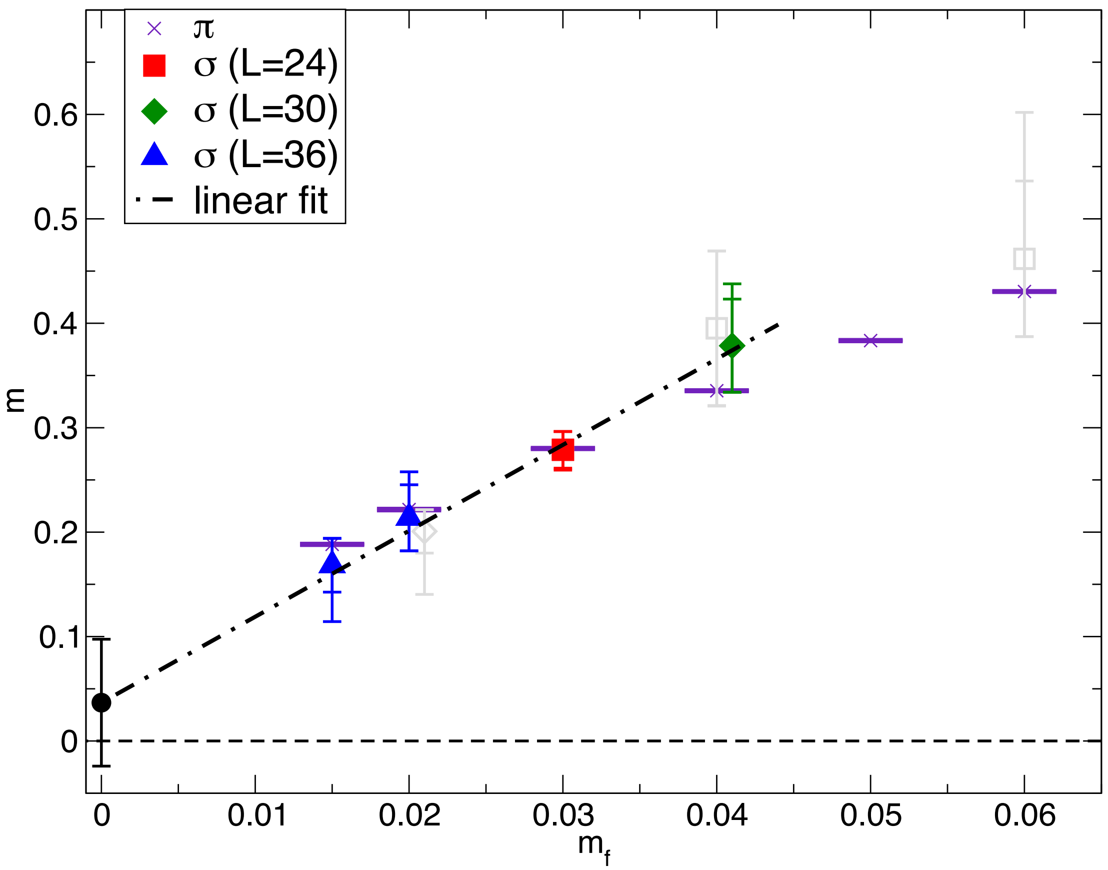


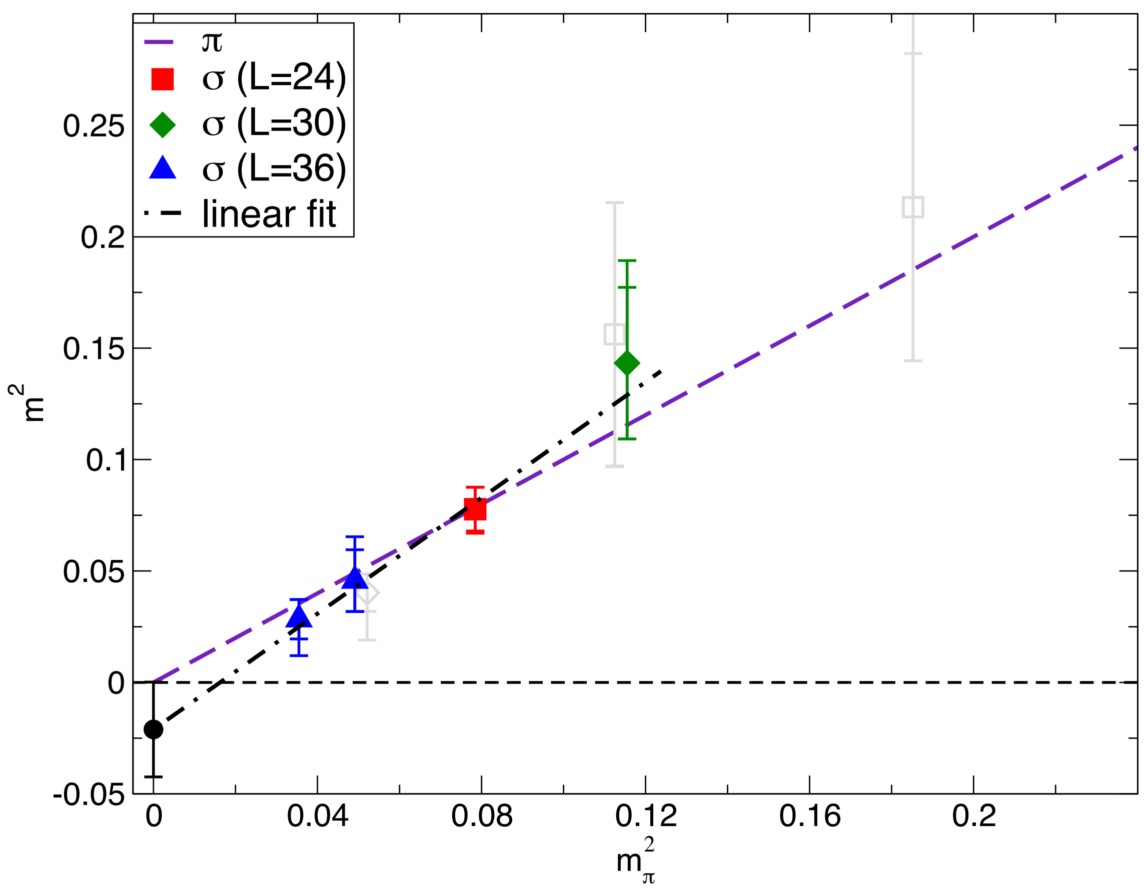
$$m_\sigma = m_0 + Am_f\text{: } m_0 = 0.038(61) \to \frac{m_\sigma}{F} = 1.7(2.8)$$

$F = 0.0219(7)$ PRD87(2013)094511

c.f.) 1 family model: $m_{\text{Higgs}} = 210(340)$ GeV

Nf=8 scalar: Update after Lattice 2013

$$m_\sigma^2 = m_0^2 + C \cdot m_\pi^2 + (\text{chiral log of } m_\pi)$$



ChPT pion and dilaton as light elements: Matsuzaki & Yamawaki '13

$m_0^2 < 0$: data not in $m_\sigma > m_\pi$ region

Need data at smaller m_f where $m_\sigma > m_\pi$ as in usual QCD

Summary and Outlook

- LatKMI collaboration is investigating the physics near the conformal phase boundary in SU(3) gauge theory.
- There appears one candidate of walking technicolor theory Nf=8 QCD, that could accommodate 125 GeV Higgs found at LHC.
- Solidness of the emerging picture will have to be investigated further:
    - precision needs to be improved
    - controversial pictures (conformality) from different collaborations
- Calculation / technology development for other quantities are underway
    - S parameter: a method proposed for vacuum polarization function
    - low energy parameters in π and σ as effective light elements...

Thank you very much for your attention !